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ATS-I SOLAR CELL RADIATION DAMAGE EXPERIMENT, FIRST 120 DAYS

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ABSTRACT

The voltage-current characteristics of 30 silicon solar cells having different base resistivities, dopants, shield materials, shield thicknesses and filters were monitored in orbit. The launch procedure, which involved one and one-half ellipses of perigee 100 nautical miles and apogee 19,300 nautical miles, caused severe damage to all unshielded cells; other cells bearing shields from 1 mil to 60 mils in thickness suffered no such damage. After attaining synchronous orbit at 19,300 nautical miles all cells suffered degradation. In 120 days all shielded cells dropped in maximum power from 4.5 to 11 percent. Tentative conclusions include: a base resistivity of 10 ohm-cm is optimum, a shield thickness of 6 mils of silica is optimum, conventional cells are superior to graded base (drift-field) cells, type 7940 silica shields are superior to type 0211 glass shields, a damage mechanism (possibly shield darkening) other than particle damage to the cell was present which led to an optimum shield thickness other than maximum.

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INTRODUCTION

Solar cells are passive solid-state diodes which can convert sunlight to electric power with an efficiency of about 10 percent. They are almost universally used, with storage batteries, to power electronic equipment on unmanned spacecraft. They are, however, subject to damage by the space environment. Energetic electrons and protons, trapped by the earth's magnetic field, are the principal damaging agents. Since the success of practically all missions on a spacecraft depends on having electric power available it is important to develop and select solar cell types which are radiation damage resistant, and which are provided with adequate transparent radiation shields. While laboratory solar cell damage experiments using energetic particles from accelerators are very useful in the development of radiation resistant cells it is not feasible to fully simulate the complex particle environment of space. It is therefore prudent to fly promising cell types on spacecraft and to closely monitor their actual space performance. Such is the objective of this experiment. This report covers the first 120 days of observations.

EXPERIMENTAL APPARATUS

The thirty nominally 1 by 2 cm solar cells involved in this experiment were mounted on a 0.125 inch thick magnesium panel, 4 by 8 inches in size. These cells, and their shields, are listed in Table 1. The cells were all of silicon, but had various base resistivities, dopants, shield materials, shield thicknesses, and filters, as shown.

Cells 1 and 2 had unfiltered artificial sapphire shields which were mechanically supported over the cells without use of an adhesive (which might darken under ultraviolet), a construction used on the solar array for Telstar. The cells were exceptionally blue sensitive and were aluminum doped. The fact that their areas were somewhat less than the other cells, and that they had no anti-reflective filters, caused their absolute power output to be less than others.

Cells 11 and 12 had a high dopant gradient in their bases. This, theoretically, generates an internal electric "drift-field" which assists the desired migration of minority carriers, supposedly minimizing their capture by defect centers. This should make them resistant to radiation damage. The cells were, of course, experimental in nature.

The cells having 10 ohm-cm base resistivities and boron doping were representative (it is believed) of modern commercial practice. The main solar array of ATS-I used cells similar to numbers 21 and 22.

The shields made of Corning type 7940 fused silica and Corning type 0211 glass were coated with blue-reflecting filters having a 400 milli-micron cut-off (to reduce darkening of the adhesive). They also had silicon monoxide anti-reflective coatings. Cells 15 and 16 had thin integral shields of Corning type 7740 glass, with no adhesives or coatings. The integral shields were applied by sintering at a high temperature. Adhesives, where used to attach shields, were Dow Corning type XR-634-88.

It will be noted that there were, generally, two cells of each type. While this number is not statistically very significant the results will show that the cells of a pair usually acted very similarly.

A 7-bit solar aspect sensor was also mounted on the "damage panel" which carried the solar cells described above. This device had a narrow angle sensor which provided a "sun-command" pulse when the azimuth angle of the spacecraft (and the damage panel) with respect to the sun passed through zero once each spin. The sensor also measured the solar aspect angle (in the plane of the spin vector) at the instant of a pulse. The pulses were also used to step relays for selecting solar cells and load resistors.

The remainder of the experiment package, which extended about 8 inches behind the damage panel, housed the 80 micro-miniature relays, a 2176 bit bi-axial magnetic core memory with associated address circuitry, an eight bit analog-to-digital converter, program circuitry for energizing the relays in proper sequence, a precision calibration voltage supply, and circuitry for presenting the memory contents by four bit words to the digital PFM telemetry system.

The entire above apparatus, in which integrated circuits and welded cord-wood modules were widely used, weighed about 5 pounds and required 5 watts of power for operation.

The memory mentioned above was necessitated by the fact that an observation of the condition of a solar cell could only be taken once per spin, and the spin rate (about 100 rpm) was, of course, non-synchronous with the telemetry rate. A memory is thus required.

The experiment was operated in the following manner. In the normal "Read" state of the memory it repeatedly presented its contents, by 4-bit

words, to the PFM telemeter. These signals were continuously recorded on magnetic tape by a ground station. One complete memory read-out required about 2.8 minutes. The information included: the solar aspect angle (by 1 degree increments), the damage panel temperature (to about 1 degree centigrade), the reading of the main telemeter clock, its reading when the memory was last filled, response to a zero signal, response to a known, fixed signal of about 480 mv, and the responses of each of the 30 solar cells as each was successively loaded by one of eight load resistors, at the instant of zero azimuth. Ground station time was also entered on the magnetic tape.

Several times a day a "Halt-Reset" command was sent from a ground station. This caused the memory to assume a "Write" state in which all old contents were discarded and a complete new set of data was entered. This took a few minutes, depending on the spin rate, after which the memory reverted to the "Read" condition in which the new information was repeatedly telemetered until again interrupted by a "Halt-Reset" command.

The use of an 8-bit analog-to-digital converter with a full scale capacity of 255 units, equivalent to 765 mv, together with the use of eight different solar cell load resistors allowed the transmission of data of sufficient accuracy and detail to permit constructing the voltage-current characteristic of each experimental solar cell. This unique capability (for a spacecraft experiment on solar cells) allows the experimenter to finally judge the condition of the cells on the basis of short-circuit current, maximum power, percent of initial maximum power, power at a given voltage, open-circuit voltage, or any other criterion of interest. This is in contrast to the usual measurement of short-circuit current, or voltage across a given load resistor, both of which can be misleading.

The telemetered data was subjected to a computer processing program which corrected the primary solar cell information to a condition of perpendicular illumination at mean earth-sun distance (nominally 140 milliwatts per square cm). It also deduced the current, voltage, and power associated with each cell as loaded with each load resistor. Lead resistances were taken into account. No attempt was made to correct data to a common temperature. A temperature difference across the damage panel of several degrees is entirely possible. The temperature at the center was read.

The received and processed data was of such consistency and repeatability as to indicate that the data transmission was occurring with an accuracy near that possible with an 8-bit digital system. Noise, ordinarily, was negligible.

THE ORBIT

The radiation damage suffered by the solar cells in this experiment was, of course, associated with the path pursued by the spacecraft ATS-I during launch procedure and while at final altitude.

The lift-off was from Cape Kennedy at year 1966, day 341, hour 02, minute 12, and seconds 02, GMT. About 20 minutes after lift-off the spacecraft was coasting freely in a transfer ellipse whose perigee was about 100 nautical miles, whose apogee was 19,300 nautical miles, and whose period was 10.7 hours. The first experiment readings were taken about 1.53 hours (0.0643 days) after lift-off, when the altitude was about 7,300 nautical miles. This initial outward pass skirted the intense portions of the inner and outer radiation belts. The spacecraft (and experiment) executed a total of one and one-half of the ellipses before being put into synchronous orbit at 19,300 nautical miles. The experimental solar cells therefore made two more passes through the belts, these times encountering more radiation. The second set of data available was taken after the experiment had been at synchronous altitude for about 2.6 days. The spacecraft then was drifting slowly westward toward its station at about 150° west longitude, over the equator.

RESULTS, TEMPERATURE AND SOLAR ASPECT

The results from this experiment will be given in the form of graphs and tables. Figure 1 shows how the temperature of the damage panel and its aspect with respect to the sun changed during the course of the experiment.

An attempt was made to select data for analysis for which the temperature was near 25° C, but this was not always available. As the Figure shows, the temperature was erratic for the first 18 days, became relatively steady until about 80 days, and then became erratic again. This behavior is caused by recurring intervals of eclipses. The step-like behavior of the temperature from 18 to 80 days is the result of digitally handling a slowly rising temperature.

It must be remembered that the solar cell responses to be given were not corrected to a constant temperature, since the required factors were not known for the great variety of cells and loading, and with different degrees of radiation damage. As is well known, however, the open-circuit voltage response of silicon solar cells has a negative temperature coefficient of about 2.3 mv per degree centigrade. The short-circuit current has a positive coefficient.

As Figure 1 shows, the attitude of the damage panel (and of the spin axis of the spacecraft) with respect to the sun changed slowly with time. Again, the steps are not real, being caused by the digital nature of the aspect sensor. The solar cell results to be given have been corrected to an aspect angle of 90 degrees (zero angle of incidence), using empirically determined correction factors for the undamaged cells while connected to the various load resistors. This information was also used in determining the corrections for varying earth-sun distance.

RESULTS, DAILY, SELECTED CELLS

A daily plot of the open-circuit voltage and the short circuit current of four selected cells is shown in Figures 2 to 5, inclusive. The data was corrected for aspect angle and earth-sun distance variations.

Figure 2 is a plot for cell 1. This is an experimental silicon n-on-p cell, 10 ohm-cm resistivity, highly blue sensitive, and doped with aluminum of high purity. The shield is 30 mils of artificial sapphire and is attached without the use of an adhesive. The plots for open-circuit voltage and short-circuit current (2000 ohm and 3 ohm load resistors, respectively) show an apparent degradation of both properties over the period of observation here reported. It will be seen that, in addition to the slow degradation, there are fluctuations during the first 18 days, and after 80 days. These fluctuations show the expected correlation with the temperature fluctuations shown in the preceding Figure. The steps in the current plot between 18 and 80 days are caused by the digital nature of the data handling. They indicate the resolution of the system.

Comparing the results for days 3 and 120, where the temperatures were the same (22.5°C), it was found that the open-circuit voltages were practically identical, while the short-circuit current fell 7.3 percent. Thus, a moderate but real degradation in current appears to have occurred in this cell during some 100 days at synchronous altitude.

Figure 3 shows daily results for cell 14. This is a silicon n-on-p cell, boron doped, of about 1 ohm-cm resistivity. It had no shield. This is the type of solar cell widely used for spacecraft power supplies before the change to higher resistivity cells.

The drop in open-circuit voltage (about 230 mv in 120 days) is far beyond that to be accounted for on a basis of temperature change. Junction damage is indicated. The voltage damage rate was high during the first 24 days after lift-off, it was low to 31 days, and high again from 31 to 40 days.

The short-circuit current of cell 14 also degraded very significantly. A rapid fall of about 15 ma during the first few days was followed by a continued slow decrease. An anomaly occurred at 50 days when the current increased slightly. Over the first 120 days the current fell about 37 percent. The drop between the first and second observations was 24 percent. This is undoubtedly associated with the second and third passes through the radiation belts which occurred during this time. These passes were much "closer" than the first one. However, it is believed that this bare cell (and others) suffered some damage during the first pass, which preceded the first observation possible. A slow degradation after these 3 passes, at synchronous altitude, is apparent.

Daily observations of cell 21 are shown in Figure 4. This cell is "modern," silicon, and boron-doped to 10 ohm-cm resistivity. It was shielded by 30 mils of 7940 silica, attached by an adhesive. It was substantially the same type of cell that was used on the main solar array of ATS-I.

The open-circuit voltage shows no significant deterioration, the slow apparent decrease being caused by the rising temperature. The short-circuit current fell significantly, about 4.5 percent, during the first 120 days.

Figure 5 shows detailed results from cell 25. This cell is very similar to cell 21, described above, except that it had no shield. A large and rapid decrease in open-circuit voltage during the first 10 days, followed by a much slower damage rate, is apparent. This damage "saturates" at a much earlier time (10 days) for this 10 ohm-cm cell than it did for the 1 ohm-cm cell 14 of Figure 3 (40 days).

The short-circuit current of 10 ohm-cm cell 25 falls about 14.5 percent during the first day, as compared with the 24 percent for the bare 1 ohm-cm cell 14.

It was remarked above that the voltage damage to cell 25 (10 ohm-cm) "saturated" sooner than it did for cell 14 (1 ohm-cm). This situation can be seen to be reversed when the short-circuit currents of these two cells are compared. This behavior no doubt reflects an interesting, but not yet fully understood, interplay between the character and energy of the damaging agents and the various damage mechanisms in the solar cells. There is a significant damage step, centered about 37 days (January 12, 1967) in the open-circuit voltage response of cell 14 and the short-circuit current response of cell 25. These, as might be expected, appear in the "least saturated" responses of each of these two cells.

RESULTS, VOLTAGE-CURRENT CURVES

Figures 6 to 21, inclusive, show the voltage-current characteristics of all of the cells in this experiment, at various times after lift-off. At the top of each graph certain additional information is provided. The mission (ATS-I) is identified. Next, the shield is described. For example, "Shield: 6-7940" indicates that the material was 6 mils (thousandths of an inch) thick and made of Corning Type 7940 fused silica. The next quantity, after "Rho," is the nominal base resistivety, in ohm-cm. The cells are identified by number, and additional information is given under "Remarks." If a single cell number is given the curves are for that cell. If two numbers are given each curve is the (visual) average of the data for those two similar cells. A cross mark on each curve indicates the point of maximum power, from whose coordinates the load resistor for maximum power may be calculated. No results are given for cell 19, which gave erratic responses, mostly zero, after a few days in orbit. The number of days in orbit at the time of observation, the temperature, and the value of maximum power are indicated near the curves. Some judgement was required in drawing the curves through (or near) the data points and there are associated uncertainties in any numerical values derived from them. The open-circuit voltage was usually quite definitely determined. All data was corrected for solar aspect and earth-sun distance variations. These corrections did not exceed 10 and 3.5 percent, respectively. No temperature corrections were attempted and this must be kept in mind in judging small changes, particularly in open-circuit voltages. Thus, for days 0.06 and 120.8 the temperature rose about 4°C. This should cause a drop of about 9 mv, which is roughly the difference observed in the responses of the shielded cells. Therefore, there was little damage to the open-circuit voltage of the shielded cells during the interval quoted. However, all of the cells show a drop in short-circuit current with time, regardless of shield or cell type. This is opposite to the expected temperature effect and is considered real and significant. Further, the decrease in maximum power is believed to be real. As the period of observation increases such statement should become more definite.

Unshielded cells 13, 14, 25, and 26 degraded greatly in open-circuit voltage, short-circuit current, and, of course in maximum power, as is evident from their voltage-current responses. The advances in solar cell technology that have occurred through the efforts of a number of government agencies and commercial firms since the start of the NASA space program can be seen graphically by comparing the responses of cell 13 (original silicon 1 ohm-cm p-on-n) with cell 14 (improved silicon 1 ohm-cm n-on-p) and with cells 25 and 26 (current 10 ohm-cm n-on-p). These

developments were largely predicated on laboratory damage studies using mono-energetic particles from accelerators. Such conditions differ greatly from those obtaining in space. It is gratifying to see the soundness of these ground studies confirmed by actual space measurements. Further developments in solar cells are in the offing and space measurements will be made as vehicles become available.

The voltage-current characteristics of the highly damaged unshielded cells remain fairly "square." They do not show the straight line resistive type of response reported as obtaining after cell damage by artificial micrometeorites.

RESULTS, TABULAR

Various solar cell parameters at different times after lift-off are shown in Table 2. These parameters were evaluated from the voltage-current curves of Figures 6 to 21.

The cell numbers are given in column 1. Table 1 may be referred to, to obtain a complete description of the cells and shields. Column 2 of Table 2 gives the figure number from which the data was read. Column 3 gives the time of observation, in days after lift-off. Column 4 gives the approximate cell temperatures. Column 5 gives the short-circuit current, in ma. This was read from the intercept of a voltage-current curve with the current axis. In some cases this value is slightly larger than the current deduced from the smallest load resistor. The latter value was used in the short-circuit current plots of Figures 2 to 5, so slight inconsistencies may be apparent. Column 6 gives the open-circuit voltage, in mv. The seventh column gives the maximum power available, with optimum load, in mw. Column 8 gives the curve factor of the cells. This is the ratio of the maximum power to the product of short-circuit current and open-circuit voltage. It is a measure of the "squareness" of the voltage-current characteristic and is sensitive to series resistance within the cell. Column 9 gives the current available at a terminal voltage of 400 mv. A parameter such as this is often used by designers of solar cell power supplies to judge the merits of solar cells. It is important because a solar array fails completely when its terminal voltage falls below the nominal voltage of the storage batteries which array usually charges. Of course, currents at other than 400 mv may be read from the curves. Column 10 gives the percentage of cell power available at the time of observation, as compared with initial capability. For all of the shielded cells, including even the 1 mil shielded cells 15 and 16, there is evidence that such cells were still substantially undamaged at the

time of the first observation at 0.0643 days, even though they had passed once through (or near) the radiation belts. The unshielded cells had suffered obvious damage at this time, so their initial, undamaged responses of 100 percent were deduced from pre-launch sunlight responses, on the ground. Giving significance to the utility of "percent initial maximum power," (Column 10) as is done in this report, tacitly assumes that all of the types of cells here tested could, with sufficient technological effort, be brought to the same initial efficiency, a debatable point.

DISCUSSION

In this experiment the various solar cells and shields were initially chosen to permit a comparison of the effects of changing certain important parameters. Table 3 consists of data extracted from Table 2 and arranged to facilitate comparisons.

Referring to this table it is seen that lines 1 to 4, inclusive, show the percent initial maximum power available at 120.8 days after lift-off of a group of cells which was nominally identical except for dopant concentration. The concentration determined the cell base resistivity. Although the range of damage is small, it appears that a resistivity of about 10 ohm-cm is optimum. This is in agreement with laboratory damage studies.

Lines 5 to 10 of Table 3 allow a comparison in which shield thickness is the variable. The shields were all of Corning Type 7940 fused silica except for the ones on cells 15 and 16, which were integral and of type 7740 glass. The table indicates an optimum shield thickness of 6 mils. This is surprising. If the degradation of cell power were caused only by internal damage by energetic particles of wide energy range the degradation should diminish indefinitely as the shield thickness was increased. Therefore, it is concluded that some damage mechanism other than particle damage to the cells was operating to cause, partly or wholly, the observed drop in power. If further observations, and experiments, should substantiate the conclusion that a shield of a few mils (possibly within the range of integral shield technology) be optimum for synchronous spacecraft solar arrays a significant advancement in this field will have been made.

It must be mentioned that a logic problem has been encountered. Observations here quoted in which base resistivity was the variable indicated an optimum value of 10 ohm-cm, in agreement with laboratory experiments in which unshielded cells were exposed to beams of damaging particles from accelerators. Yet we here also find in the orbital comparison of various shield thicknesses an optimum other than maximum, which

is contrary to the idea that the damage was (wholly) due to a spectrum of particles.

A solution to this predicament (if real) is to postulate that cell power degraded in orbit both from true particle damage to the cell (which should get less as the shield thickness is increased) and to some other factor which gets more detrimental as the thickness is increased. This could lead to an optimum thickness, as observed. The factor could hardly be darkening of the shield adhesive or damage to the surface antireflecting film. Micrometeoroid erosion at synchronous altitude seems improbable. The apparent increase in cell damage observed when the cell shields were increased beyond 6 mils in thickness could have been caused by such shields slowing down some strong high energy component of the incident proton spectrum. The resulting lower energy protons would be more highly damaging than the original more energetic ones, as is well known. However, this theory requires a special shape for the original proton energy spectrum.

Another possibility is that the larger damage observed with thicker shields was caused by shield darkening under ultraviolet or particle irradiation. As the shield thickness was increased a greater amount of the available incident energy of these radiations becomes absorbed by the shield. If this absorption caused darkening (as is known to occur to some degree) then thicker shields would increasingly reduce the amount of light reaching the amount of light reaching the solar cell, and, consequently, its power output. The result of considering cell damage by particles, and shield damage by radiations could thus lead to an optimum thickness. It is tentatively concluded that this is the situation in this experiment.

In Table 3 one may compare lines 11 and 12. These contrast cells 1 and 2, of special blue-sensitive construction with aluminum doping and carrying sapphire shields with no adhesive or filters with a conventional boron doped cell (number 20) bearing an adhesively mounted 60 mil 7940 silica shield, with filters. The sapphire shield had about the same particle stopping power as the thicker silica shield, because of its greater density. It is seen that the damage to both of these types of cell was severe, and one type of construction had no great advantage over the other.

In lines 13 and 14 of the table nominally identical cells bearing 6 mil shields of 7940 silica and of 0211 "Microsheet" glass are constrasted. The 7940 silica appears to be superior. Laboratory studies have indicated such superiority with respect to radiation darkening.

Lines 15 and 16 compare conventional silicon cells 5 and 6 with cells 11 and 12, which are of "graded base" or "drift-field" construction. The built-in electric field of the latter theoretically assists the desired migration of minority carriers in the base, and decreases the probability of their being trapped by defects created by damaging radiations. However, these cells appear inferior, at this damage level, to the cells of conventional construction. In spite of the radical doping they have good curve factors and a very high open-circuit voltage, as may be seen from Table 2. Incidentally, it may be seen from this table that the curve factors almost always decrease after damage to cells. This is in contrast to certain electron accelerator experiments that have been reported in which the curve factor increased.

Lines 17 and 18 of Table 3 contrast cells which were nominally identical except that the dopants were aluminum or boron. The aluminum doping appears slightly superior. It should be noted that the shields were not of "optimum" thickness.

Lines 19 and 20 compare aluminum doped cells carrying shields of 6 mils of silica with others carrying 30 mil shields. The thicker shields here appear more effective. It will be recalled that the situation was reversed for boron doped cells. Thus the nature of the doping appears to alter the balance between true cell radiation damaged and apparent damage caused by shield darkening, if the latter is actually a significant factor.

CONCLUSIONS

It must be emphasized that only after amounts of damage that well exceed uncertainties have occurred that firm and valid conclusions may be attempted. Even then, the number of solar cells here tested is statistically small, and conceivably the cells flown were not representative. Uncontrolled variations may lead to incorrect conclusions. Finally, these data, and therefore any conclusions drawn from them, are valid only for an environmental history similar to that of the spacecraft here employed (ATS-I, 661101).

The tentative conclusions are summarized below.

(a) Unshielded silicon solar cells were highly damaged during the launch procedure (3 passages through the radiation belts) here employed, and continued to degrade at synchronous altitude.

(b) Unshielded silicon 1 ohm-cm p-on-n cells, 1 ohm-cm n-on-p cells, and 10 ohm-cm n-on-p cells were, in that order, increasingly resistant to radiation damage.

(c) Cells bearing shields of 1 mil thickness or greater suffered no apparent damage during the launch procedure but degraded slowly at synchronous altitude. Maximum power dropped over a range of 4.5 percent to 11 percent in 120.8 days.

(d) For boron doped silicon cells carrying shields of 7940 silica the optimum shield thickness was 6 mils.

(e) For boron doped silicon cells bearing 6 mil shields of 7940 silica the optimum base resistivity was 10 ohm-cm.

(f) Special cell construction, using high purity aluminum doping to a 10 ohm-cm level and non-adhesively mounted artificial sapphire shields showed no advantage over conventional 10 ohm-cm boron doped cells bearing 7940 silica adhesively mounted shields of comparable stopping power.

(g) Shields of 7940 silica, 6 mils thick were superior to those of 0211 glass of the same thickness.

(h) The "graded base" or "drift-field" construction is inferior to conventional construction, at the damage levels here observed.

(i) Aluminum doped cells are superior to boron doped cells of otherwise similar construction, both having 30 mil 7940 shields.

(j) Aluminum doped 10 ohm-cm silicon cells with 30 mil silica shields are superior to such cells with 6 mil shields.

(k) The most highly damage resistant cells, when judged either on a basis of percent of maximum initial power or absolute maximum power, were conventional 10 ohm-cm boron doped cells bearing 6 mil shields of 7940 silica, adhesively mounted and equipped with ultraviolet rejecting, and antireflecting filters.

(l) Certain unshielded cells showed a high damage rate in an interval centered around 37 days after lift-off.

(m) The apparent cell damage observed in this experiment was probably caused, at least in part, by some mechanism other than energetic particle damage to the cell proper. This mechanism was of such nature that it became more deleterious with shield thickness. It could be shield darkening under irradiation. It led to the existence of an optimum shield thickness other than maximum.

Table 1
ATS-I Solar Cell Description

Solar Cell Number	Type	Base Resistivity (ohm-cm)	Dopant	Shield Material	Shield Thickness (mils)
1,2	n/p	10	AL	Sapphire	30
3,4	n/p	13	B	7940 silica	6
5,6	n/p	10	B	7940 silica	6
7,8	n/p	7	B	7940 silica	6
9,10	n/p	3	B	7940 silica	6
11,12	n/p	Graded	B	7940 silica	6
13	p/n	1	P	None	0
14	n/p	1	B	None	0
15,16	n/p	10	B	7740 glass	1
17,18	n/p	10	B	0211 glass	6
19,20	n/p	10	B	7940 silica	60
21,22	n/p	10	B	7940 silica	30
23,24	n/p	10	B	7940 silica	15
25,26	n/p	10	B	None	0
27,28	n/p	10	AL	7940 silica	30
29,30	n/p	10	AL	7940 silica	6

Table 2

ATS-I Solar Cell Characteristics, After Lift-Off

(1) Cell No.	(2) Figure No.	(3) Time After Lift-Off (days)	(4) Temp (°C)	(5) I_{sc} (ma)	(6) V_{oc} (mv)	(7) Max. P, (mw)	(8) Curve Factor	(9) I At 400 mv (ma)	(10) P Max % Initial
1,2	6	0.0643	18.8	46.0	533	18.0	0.735	44.2	100.0
3,4	7	0.0643	18.8	63.8	556	24.6	0.693	59.9	100.0
5,6	8	0.0643	18.8	67.7	569	27.9	0.725	65.0	100.0
7,8	9	0.0643	18.8	62.9	573	25.9	0.718	60.7	100.0
9,10	10	0.0643	18.8	61.4	589	25.9	0.717	58.9	100.0
11,12	11	0.0643	18.8	55.9	600	24.1	0.720	54.1	100.0
13	12	0.0643	18.8	57.9	563	21.7	0.667	52.7	92.9
14	13	0.0643	18.8	53.7	569	19.6	0.641	48.9	92.0
15,16	14	0.0643	18.8	62.2	554	24.9	0.736	59.7	100.0
17,18	15	0.0643	18.8	66.6	573	27.8	0.729	65.0	100.0
20	16	0.0643	18.8	68.8	575	28.7	0.726	66.9	100.0
21,22	17	0.0643	18.8	68.8	570	28.5	0.726	67.2	100.0
23,24	18	0.0643	18.8	67.4	573	27.6	0.715	65.3	100.0
25,26	19	0.0643	18.8	69.8	559	27.6	0.718	67.5	97.1
27,28	20	0.0643	18.8	66.9	570	27.4	0.700	64.1	100.0
29,30	21	0.0643	18.8	64.0	568	26.2	0.721	61.7	100.0
1,2	6	120.8	22.5	43.3	520	16.2	0.719	41.1	90.0
3,4	7	120.8	22.5	61.1	544	22.3	0.670	54.9	90.8
5,6	8	120.8	22.5	64.8	560	26.6	0.733	62.4	95.5
7,8	9	120.8	22.5	60.9	557	24.0	0.691	56.1	92.5
9,10	10	120.8	22.5	59.1	573	23.4	0.691	51.0	90.3
11,12	11	120.8	22.5	53.5	588	22.3	0.710	51.5	92.6
13	12	120.8	22.5	12.9	228	1.7	0.578	0.0	7.3
14	13	120.8	22.5	34.0	327	5.6	0.504	0.0	26.2
15,16	14	120.8	22.5	58.7	534	22.3	0.712	55.0	89.5
17,18	15	120.8	22.5	65.0	560	26.0	0.714	62.0	93.5
20	16	120.8	22.5	66.9	565	25.6	0.678	62.2	89.2
21,22	17	120.8	22.5	66.0	568	26.2	0.712	62.8	91.9
23,24	18	120.8	22.5	65.5	562	25.6	0.695	61.1	92.9
25,26	19	120.8	22.5	40.1	315	6.2	0.495	0.0	21.8
27,28	20	120.8	22.5	63.7	560	25.9	0.726	61.1	94.5
29,30	21	120.8	22.5	61.6	559	23.8	0.691	56.9	90.9

Table 3
Solar Cell Comparisons 120.8 Days After Lift-Off

LINE	CELL NUMBER	BASE RESISTIVITY (ohm-cm)	SHIELD	DOPANT	PERCENT INITIAL POWER
1	9, 10	3	6, 7940	B	90. 3
2	7, 8	7	6, 7940	B	92. 5
3	5, 6	10	6, 7940	B	95. 5
4	3, 4	13	6, 7940	B	90. 8
5	25, 26	10	NONE	B	21. 8
6	15, 16	10	1, 7740	B	89. 5
7	5, 6	10	6, 7940	B	95. 5
8	23, 24	10	15, 7940	B	92. 9
9	21, 22	10	30, 7940	B	91. 9
10	20	10	60, 7940	B	89. 2
11	1, 2	10	30, SAP.	AL	90. 0
12	20	10	60, 7940	B	89. 2
13	5, 6	10	6, 7940	B	95. 5
14	17, 18	10	6, 0211	B	93. 5
15	5, 6	10	6, 7940	B	95. 5
16	11, 12	GRADED	6, 7940	B	92. 6
17	21, 22	10	30, 7940	B	91. 9
18	27, 28	10	30, 7940	AL	94. 5
19	29, 30	10	6, 7940	AL	90. 9
20	27, 28	10	30, 7940	AL	94. 5

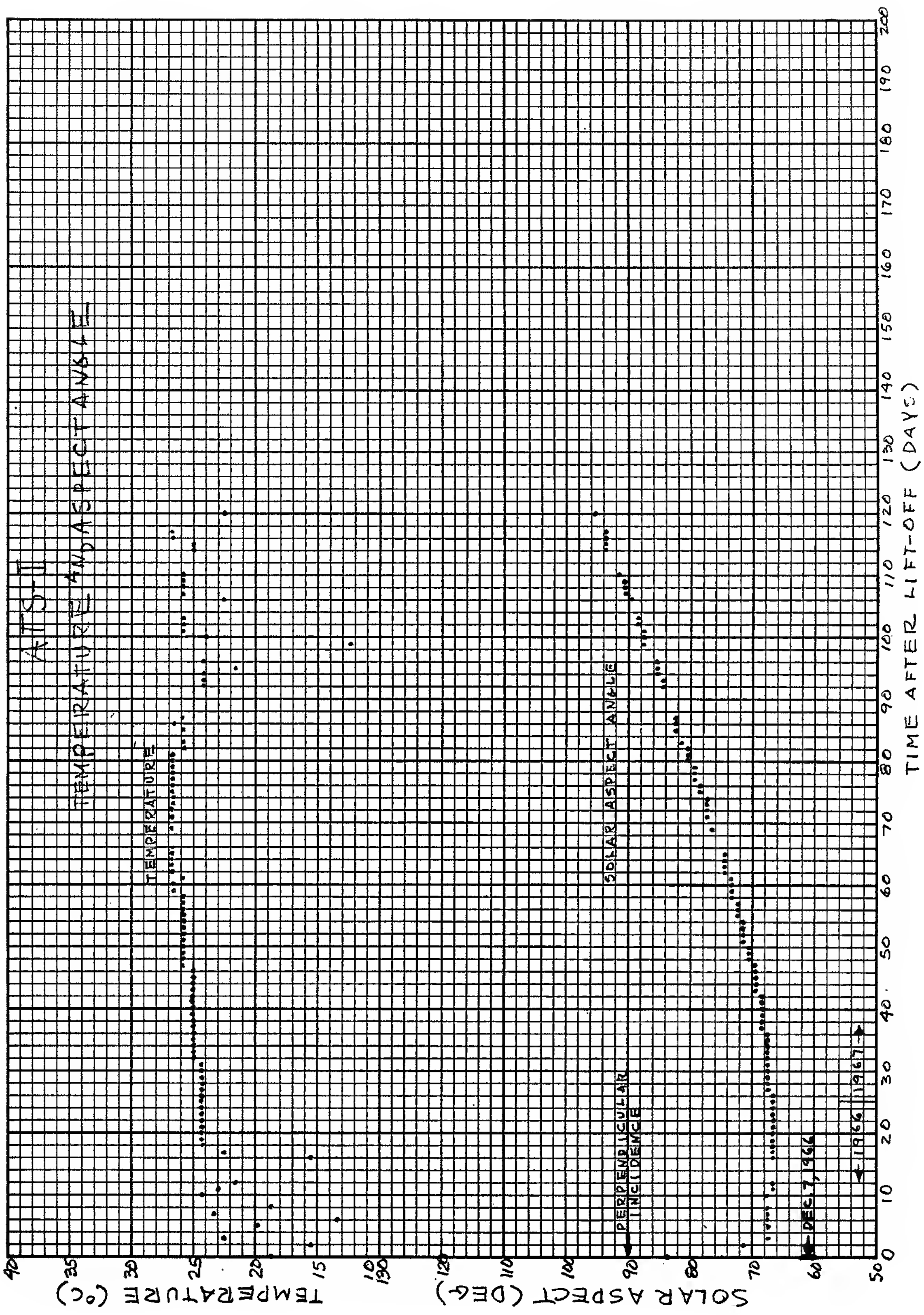
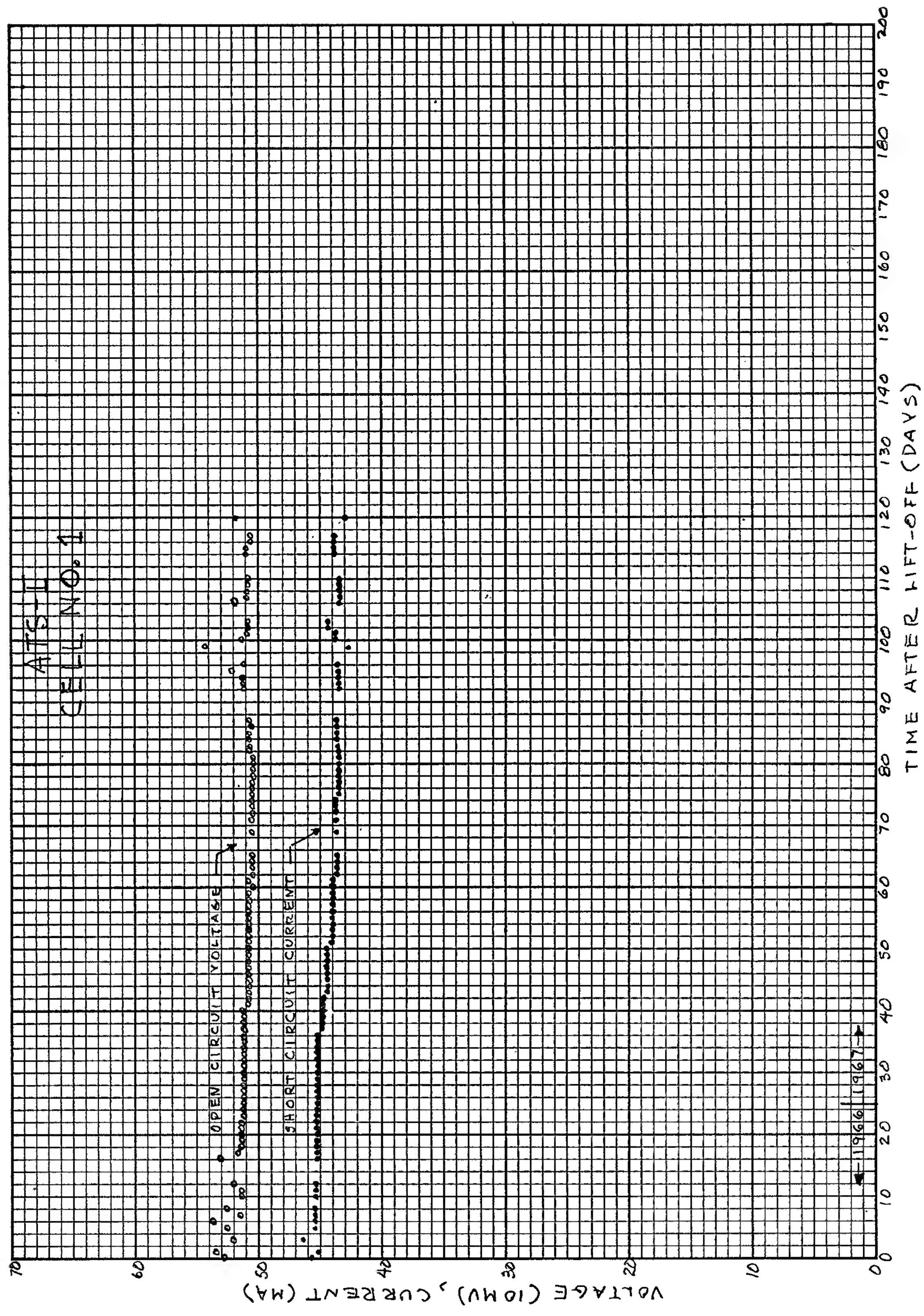

ATS-II
TEMPERATURE AND ASPECT ANGLE
TEMPERATURE
SOLAR ASPECT ANGLE
PERPENDICULAR INCIDENCE
DEC. 7, 1966
1966
1967
TIME AFTER LIFT-OFF (DAYS)
TEMPERATURE (°C)
SOLAR ASPECT (DEG.)

Figure 1



ATS-1
CELL NO. 1
OPEN CIRCUIT VOLTAGE
SHORT CIRCUIT CURRENT
1966
1967
TIME AFTER LIFT-OFF (DAYS)
VOLTAGE (10 MV), CURRENT (MA)
0 10 20 30 40 50 60 70 80 90 100 110 120 130 140 150 160 170 180 190 200
0 10 20 30 40 50 60 70

Figure 2

ATS-I
CELL NO. 14
SHORT CIRCUIT CURRENT
OPEN CIRCUIT VOLTAGE
1966
1967
TIME AFTER LIFT-OFF (DAYS)
VOLTAGE (10MV), CURRENT (MA)

Figure 3

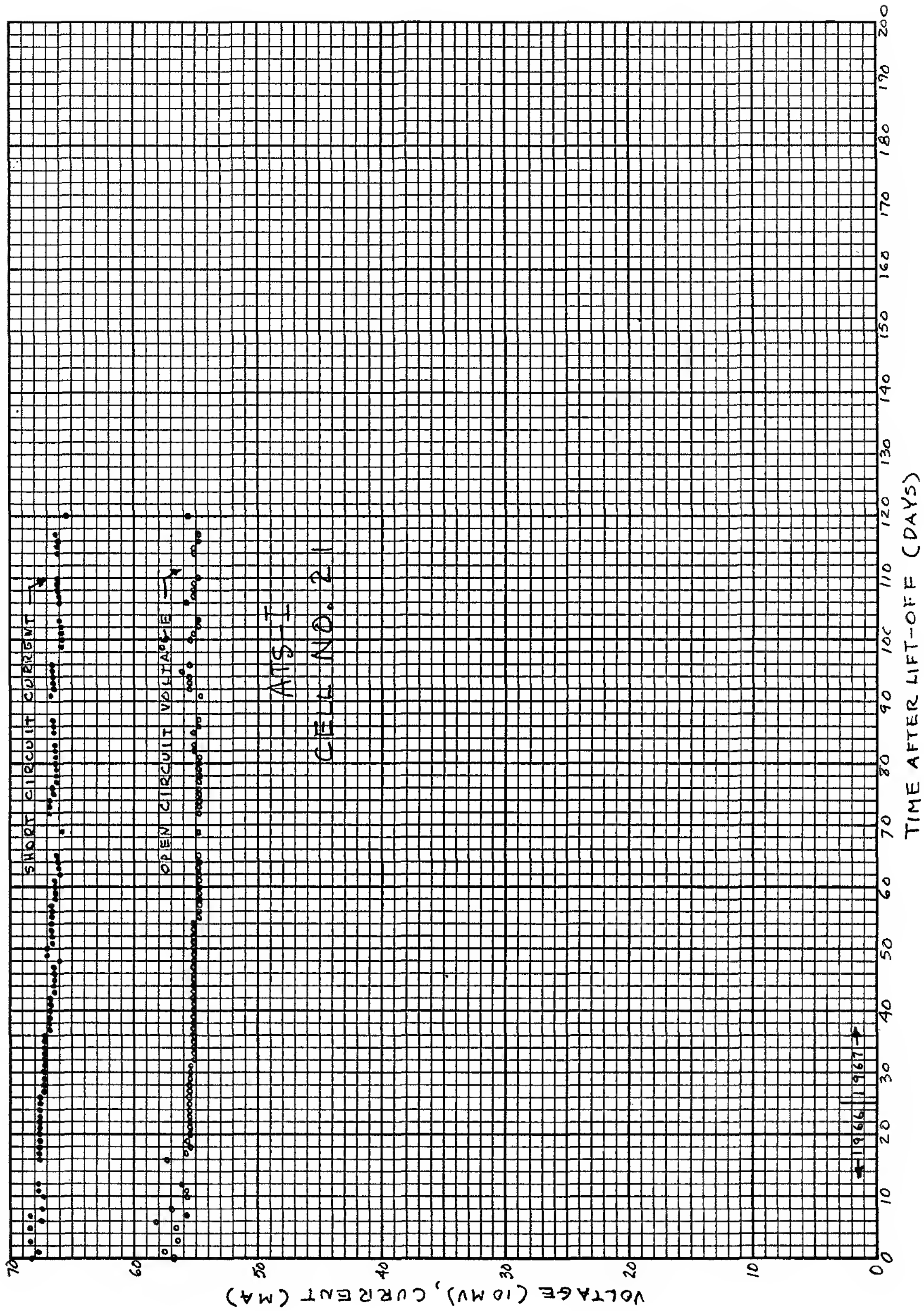

SHORT CIRCUIT CURRENT
OPEN CIRCUIT VOLTAGE
ATS-I
CELL NO. 21
←1966 | 1967→
0 10 20 30 40 50 60 70 80 90 100 110 120 130 140 150 160 170 180 190 200
TIME AFTER LIFT-OFF (DAYS)
0 10 20 30 40 50 60 70
VOLTAGE (10 MV), CURRENT (MA)

Figure 4

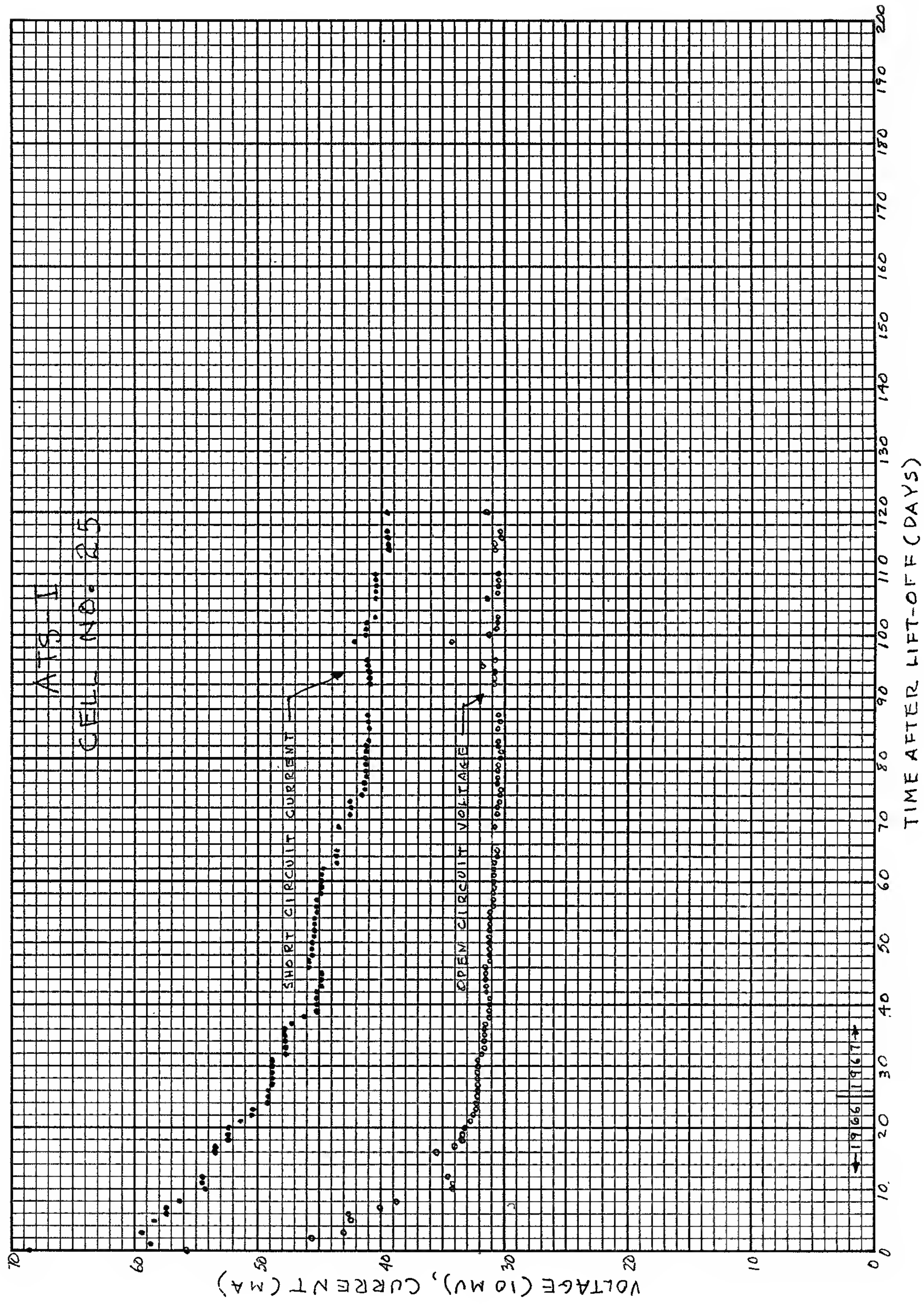

ATS-I
CELL NO. 25
SHORT CIRCUIT CURRENT
OPEN CIRCUIT VOLTAGE
1966
1967
TIME AFTER LIFT-OFF (DAYS)
VOLTAGE (10 MV), CURRENT (MA)

Figure 5

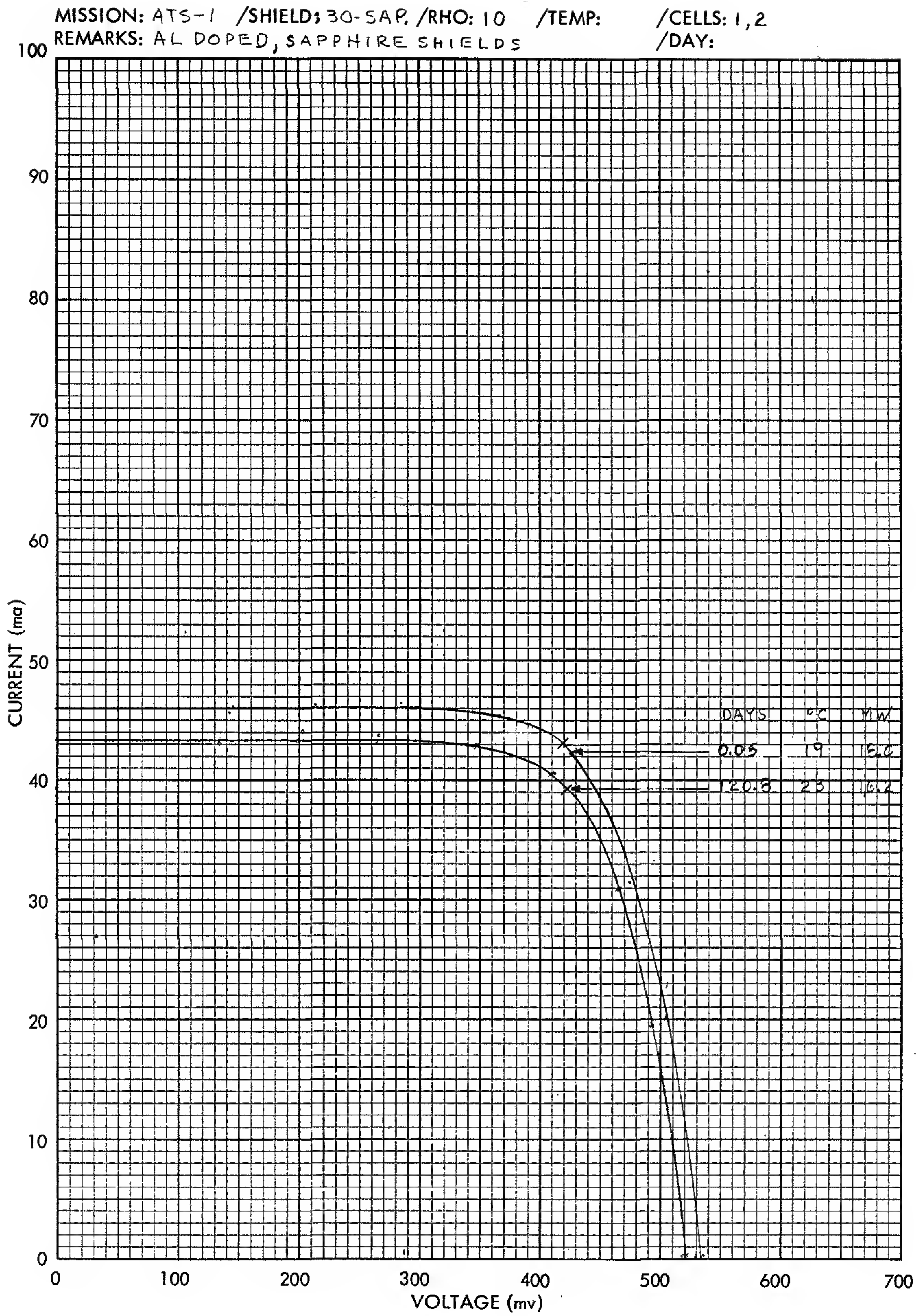
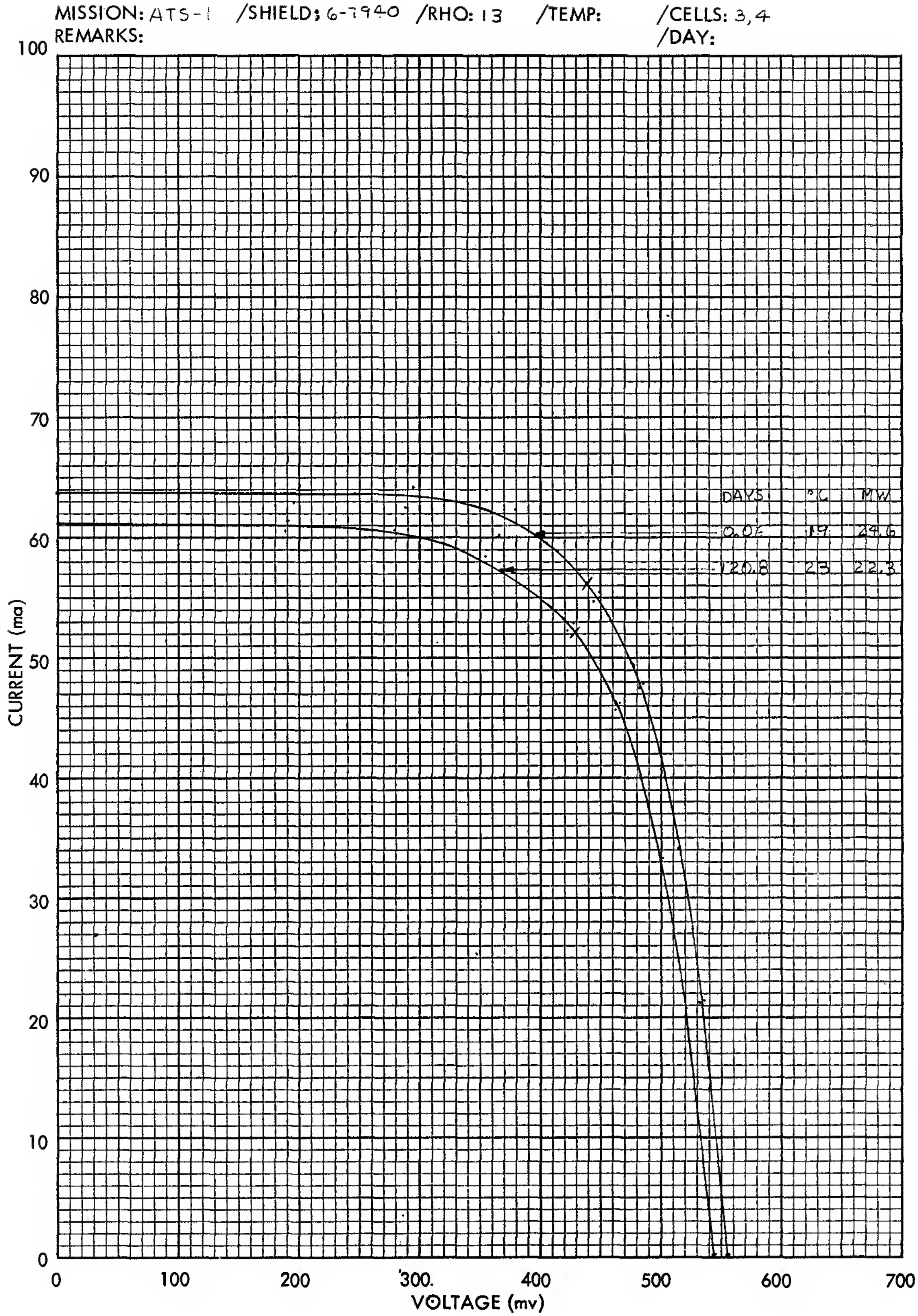
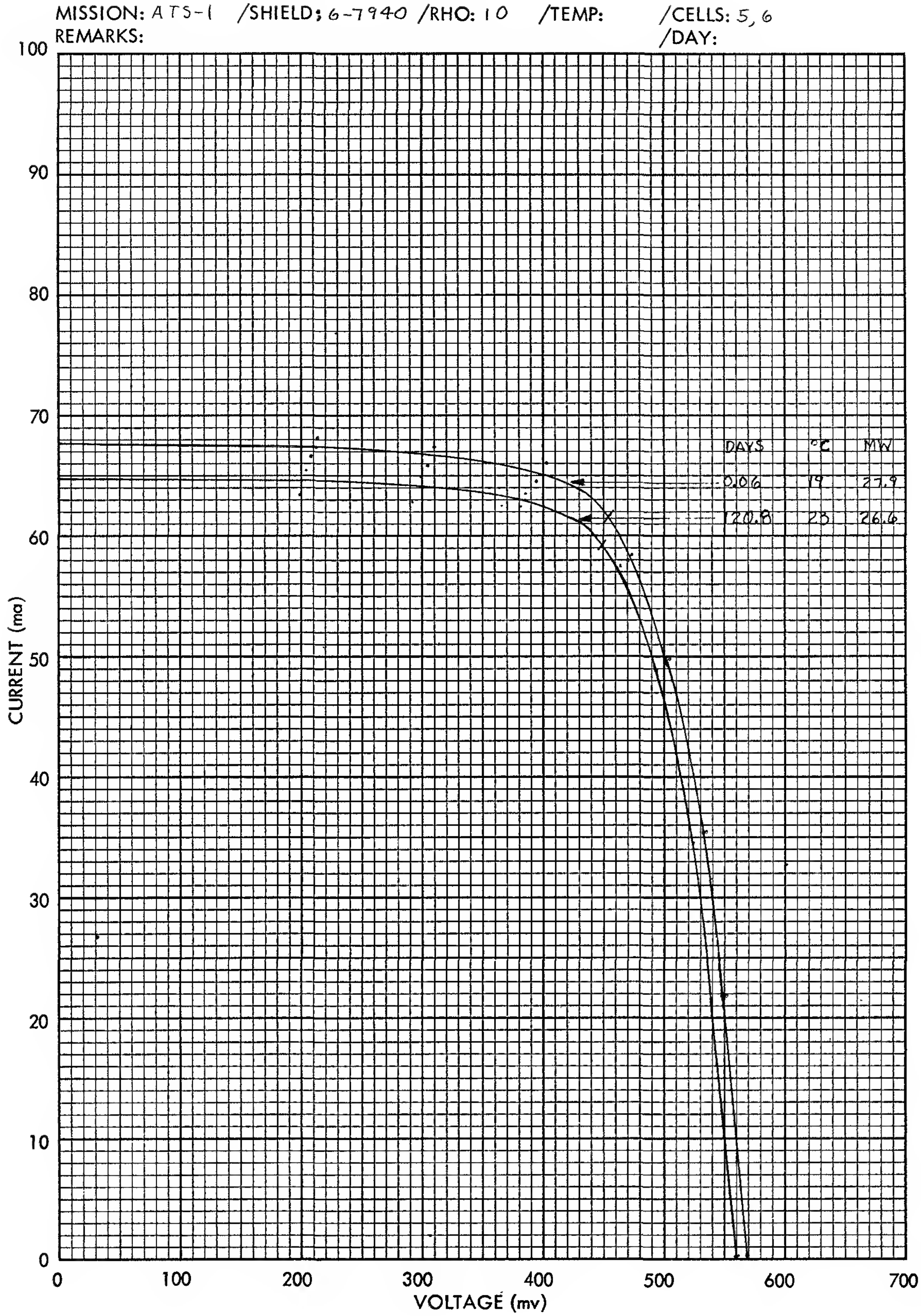

MISSION: ATS-1 /SHIELD: 30-SAP. /RHO: 10 /TEMP: /CELLS: 1,2
REMARKS: AL DOPED, SAPPHIRE SHIELDS /DAY:
CURRENT (ma)
VOLTAGE (mv)
DAYS °C MW
0.05 19 16.0
120.8 23 16.2
0 100 200 300 400 500 600 700
0 10 20 30 40 50 60 70 80 90 100

Figure 6



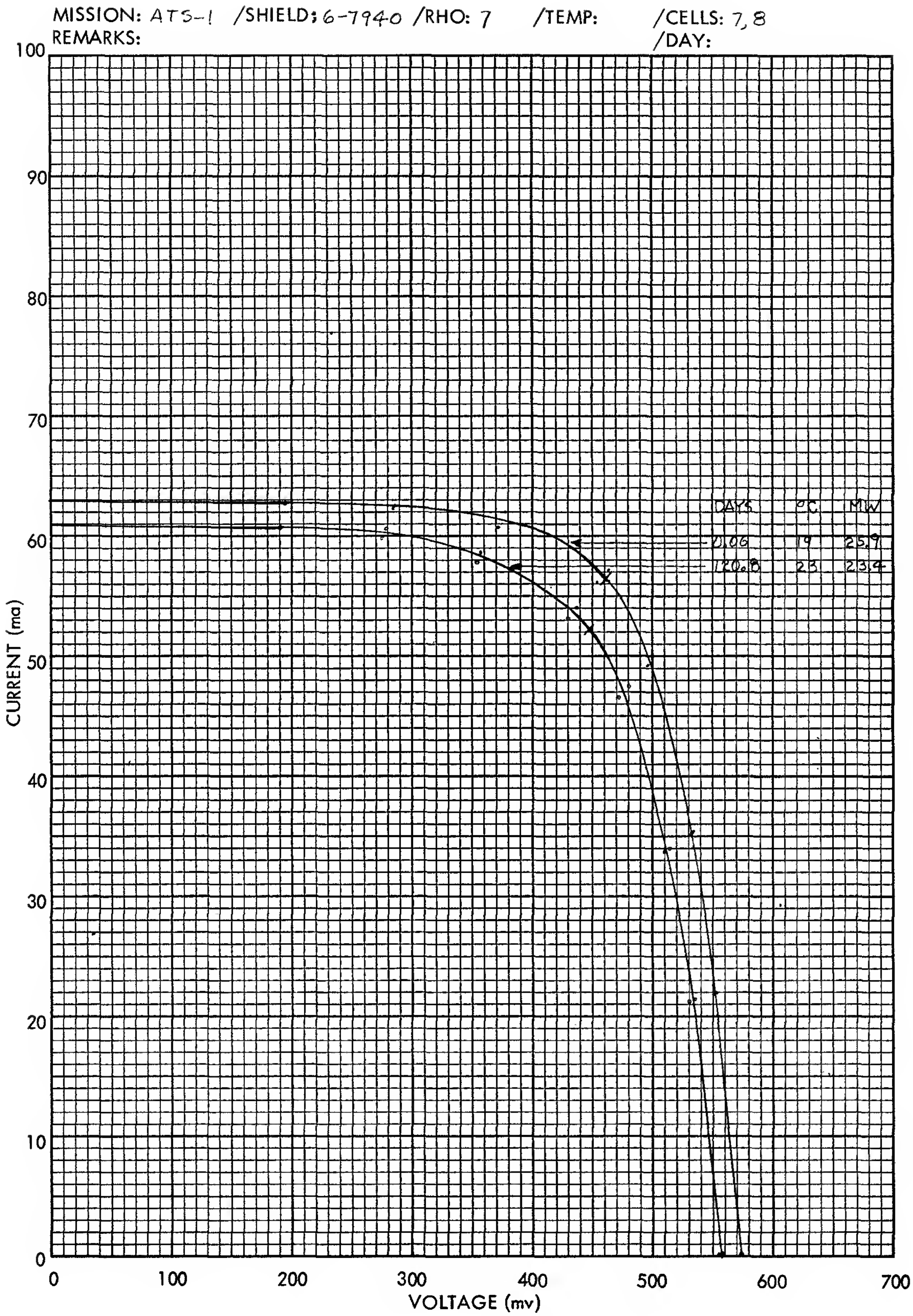
MISSION: ATS-1 /SHIELD; 6-7940 /RHO: 13 /TEMP: /CELLS: 3,4
REMARKS: /DAY:
CURRENT (ma)
VOLTAGE (mv)
100
90
80
70
60
50
40
30
20
10
0
100
200
300
400
500
600
700
DAYS °C MW
0.06 19 24.6
120.8 23 22.3

Figure 7



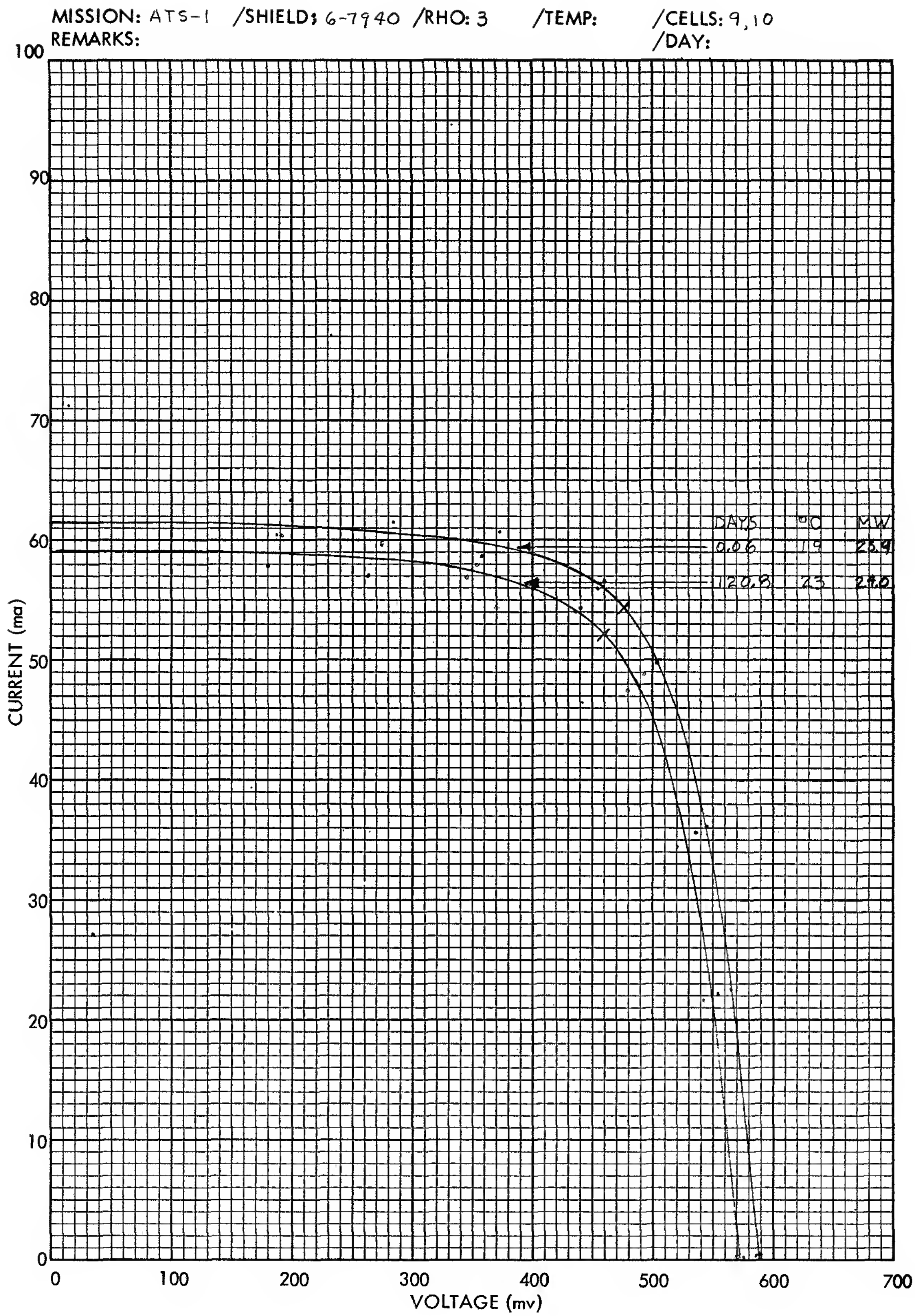
MISSION: ATS-1 /SHIELD; 6-7940 /RHO: 10 /TEMP: /CELLS: 5, 6
REMARKS: /DAY:
CURRENT (ma)
VOLTAGE (mv)
DAYS °C MW
0.06 19 27.9
120.8 23 26.6

Figure 8



MISSION: ATS-1 /SHIELD; 6-7940 /RHO: 7 /TEMP: /CELLS: 7,8
REMARKS: /DAY:
DAYS °C MW
0.06 19 25.9
120.8 23 23.4
CURRENT (ma)
VOLTAGE (mv)
0
10
20
30
40
50
60
70
80
90
100
100
200
300
400
500
600
700

Figure 9



MISSION: ATS-1 /SHIELD: 6-7940 /RHO: 3 /TEMP: /CELLS: 9,10
REMARKS: /DAY:
DAYS °C MW
0.06 19 25.9
120.8 23 24.0
CURRENT (ma)
VOLTAGE (mv)
0
10
20
30
40
50
60
70
80
90
100
0
100
200
300
400
500
600
700

Figure 10

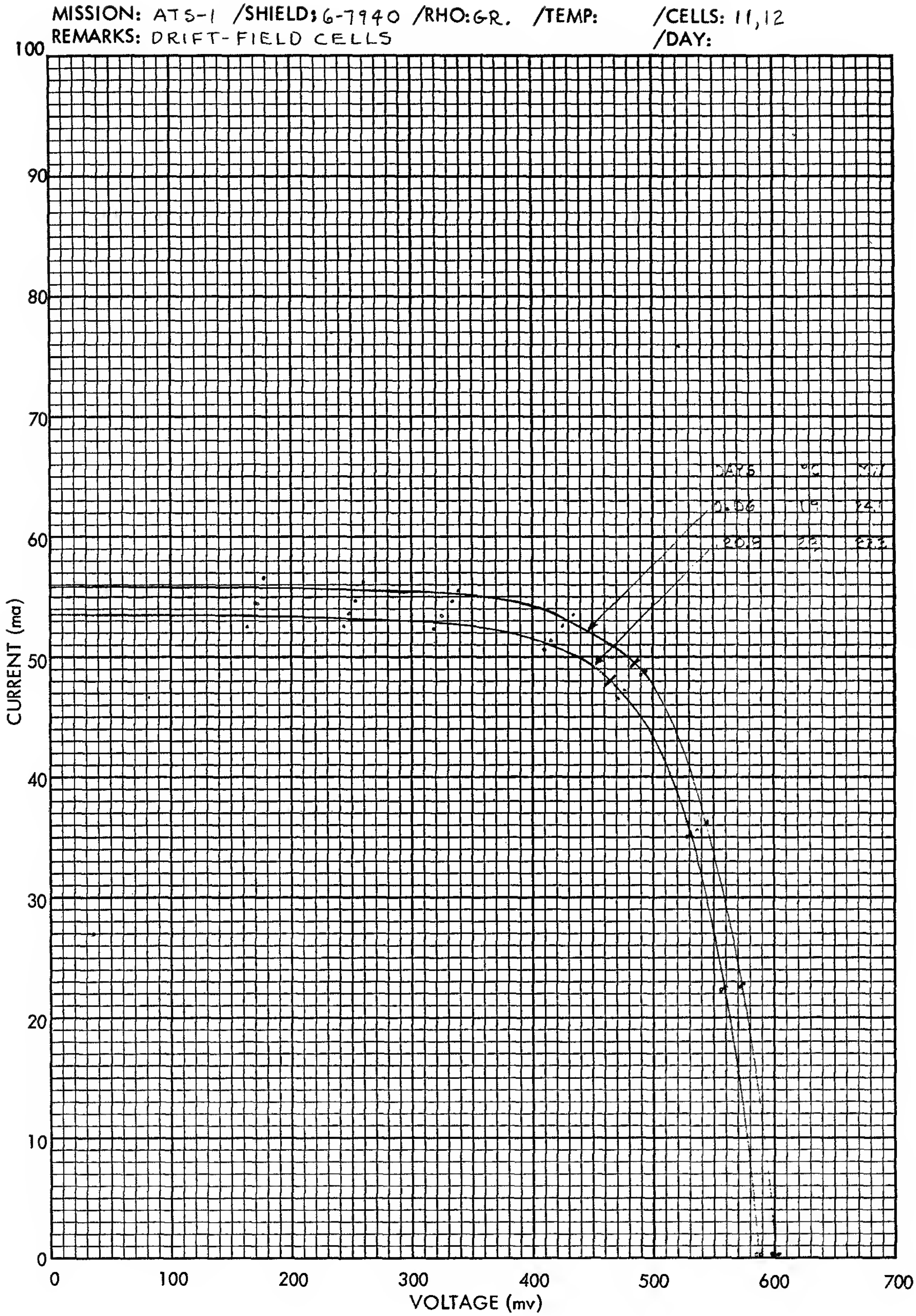

MISSION: ATS-1 /SHIELD: 6-7940 /RHO: GR. /TEMP: /CELLS: 11,12
REMARKS: DRIFT-FIELD CELLS /DAY:
DAYS
°C
0.06
20.9
CURRENT (ma)
VOLTAGE (mv)
0
10
20
30
40
50
60
70
80
90
100
0
100
200
300
400
500
600
700

Figure 11

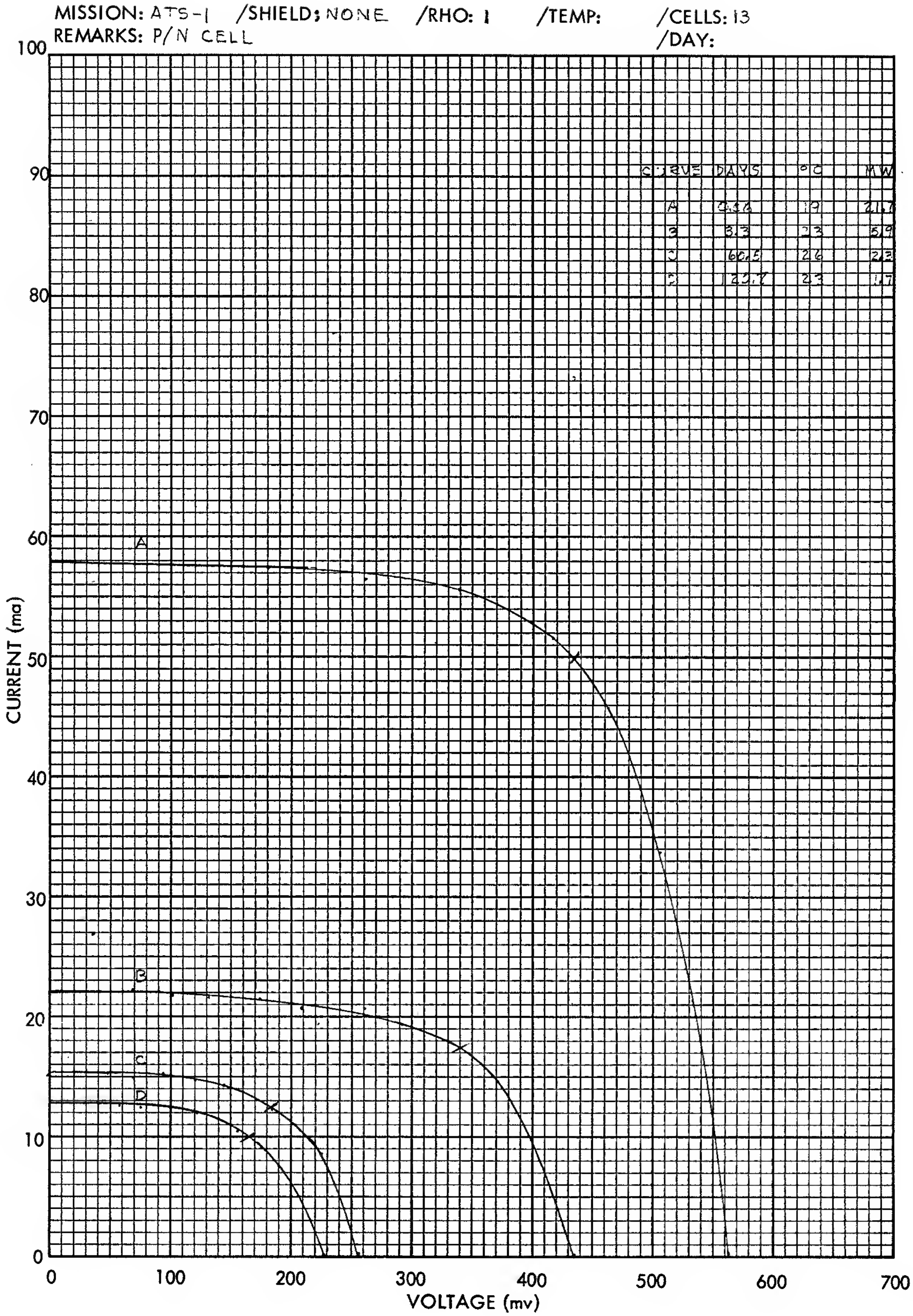

MISSION: ATS-1 /SHIELD; NONE /RHO: 1 /TEMP: /CELLS: 13
REMARKS: P/N CELL /DAY:
CURRENT (ma)
VOLTAGE (mv)
0
10
20
30
40
50
60
70
80
90
100
100
200
300
400
500
600
700
CURVE DAYS °C MW
A 19 21.7
B 3.3 23 5.9
C 60.5 26 2.3
D 23 1.7
A
B
C
D

Figure 12

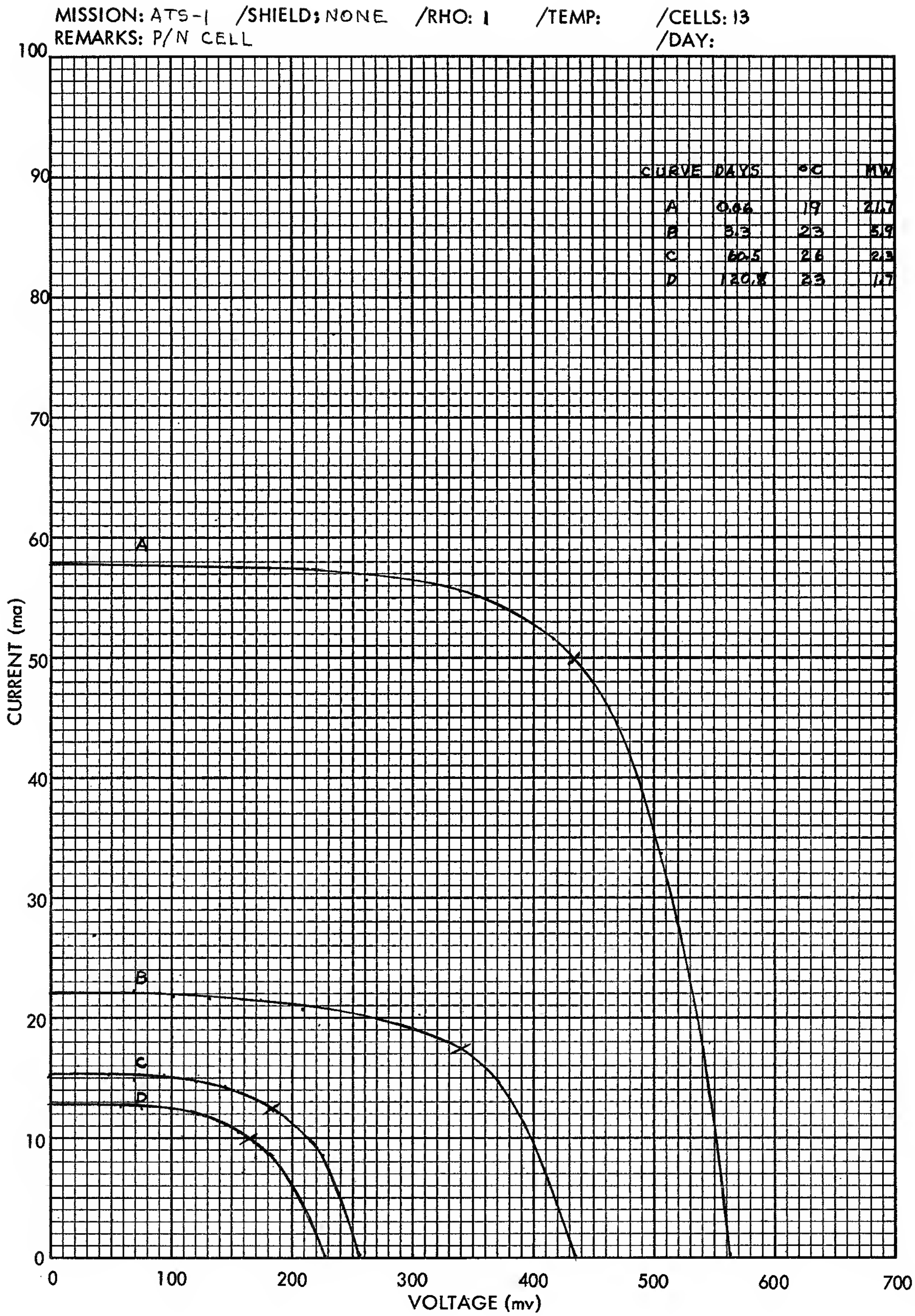
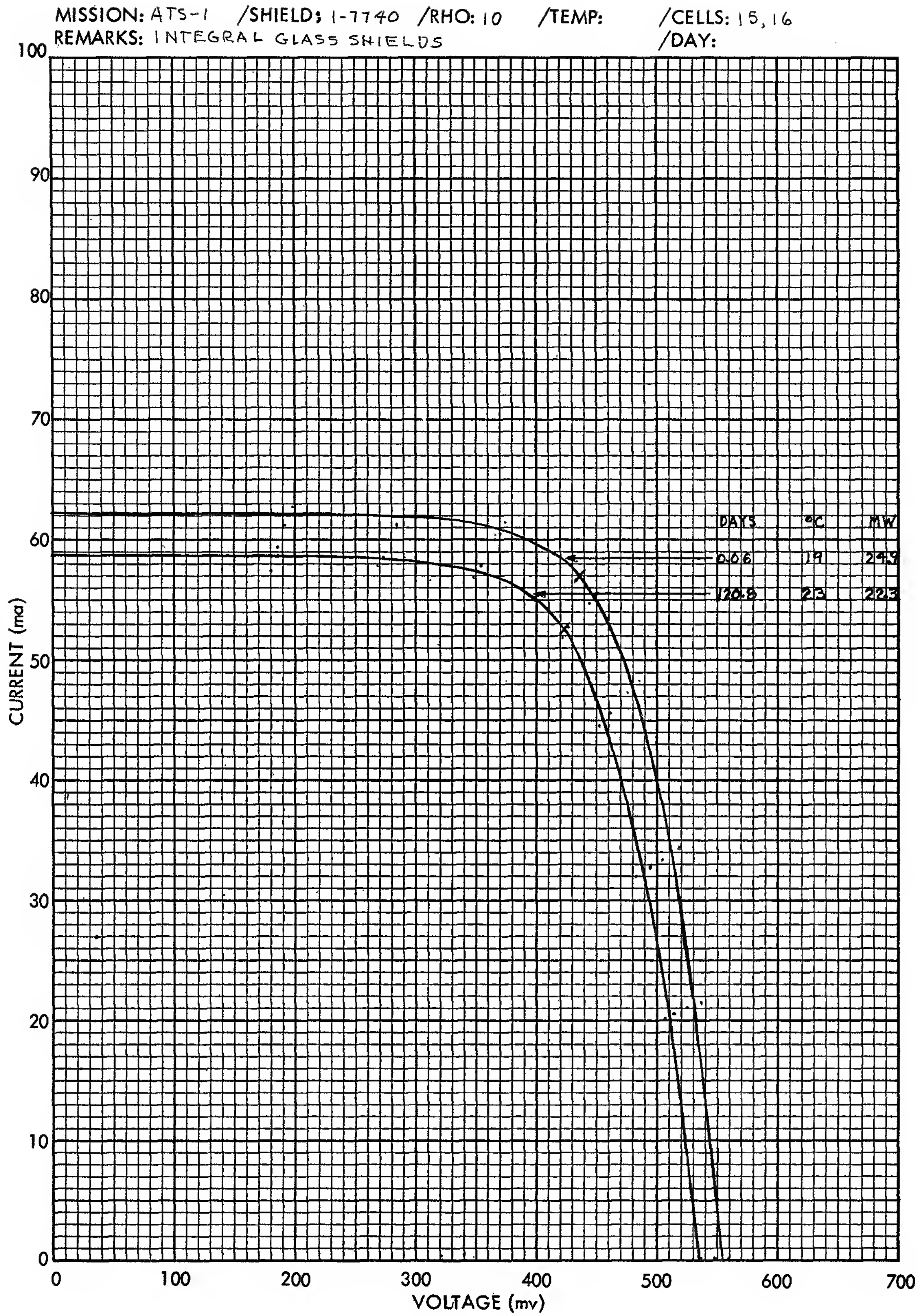

MISSION: ATS-1 /SHIELD: NONE /RHO: 1 /TEMP: /CELLS: 13
REMARKS: P/N CELL /DAY:
CURVE DAYS °C MW
A 0.66 19 21.7
B 5.3 23 5.9
C 60.5 26 2.3
D 120.8 23 1.7
A
B
C
D
CURRENT (ma)
100
90
80
70
60
50
40
30
20
10
0
0
100
200
300
400
500
600
700
VOLTAGE (mv)

Figure 13



MISSION: ATS-1 /SHIELD: 1-7740 /RHO: 10 /TEMP: /CELLS: 15, 16
REMARKS: INTEGRAL GLASS SHIELDS /DAY:
DAYS °C MW
0.06 19 24.9
120.8 23 22.3
CURRENT (ma)
VOLTAGE (mv)
0
10
20
30
40
50
60
70
80
90
100
0
100
200
300
400
500
600
700

Figure 14

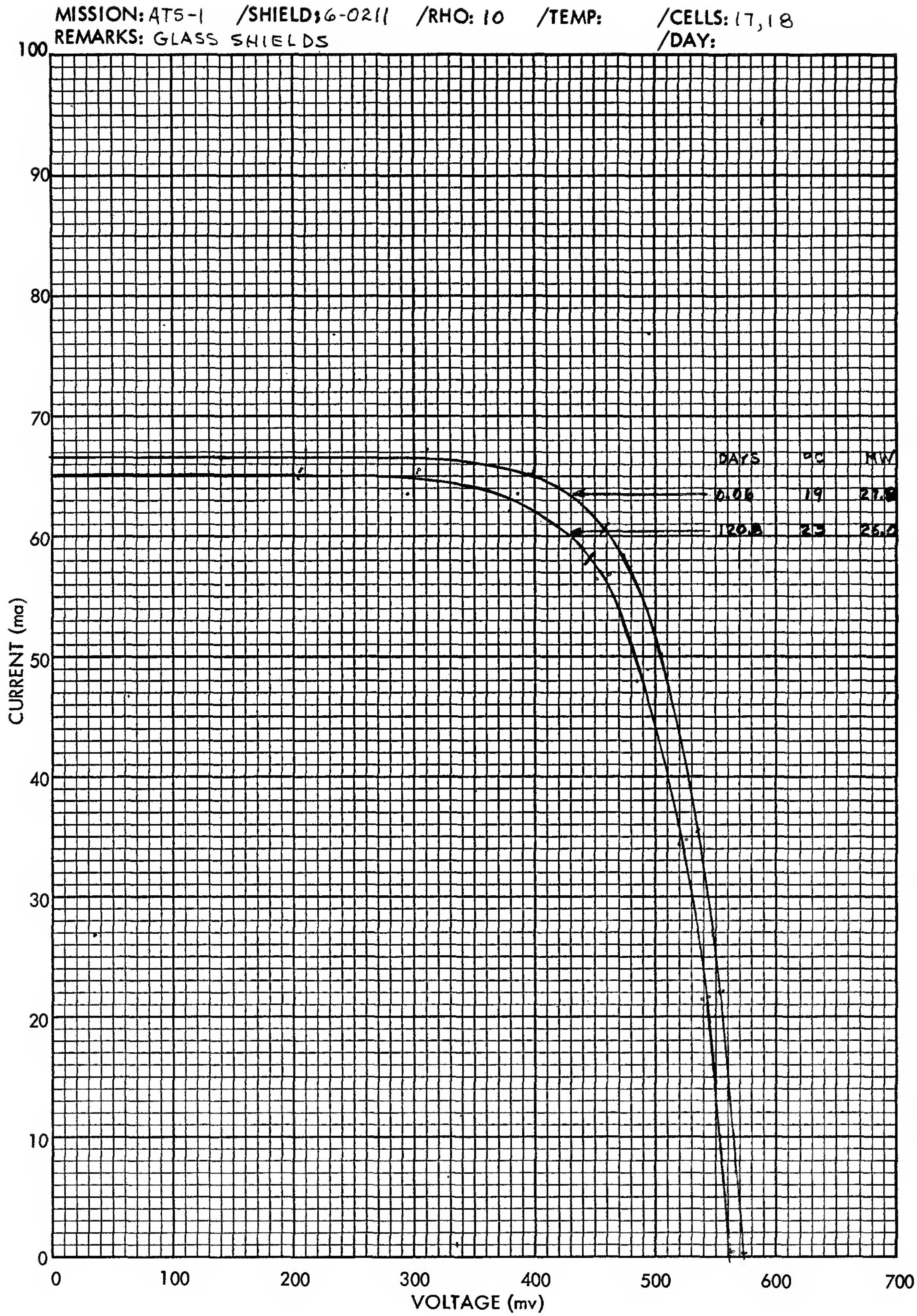

MISSION: ATS-1 /SHIELD: 6-0211 /RHO: 10 /TEMP: /CELLS: 17, 18
REMARKS: GLASS SHIELDS /DAY:
CURRENT (ma)
VOLTAGE (mv)
0
10
20
30
40
50
60
70
80
90
100
0
100
200
300
400
500
600
700
DAYS
°C
MW
0.06
19
26.0

Figure 15

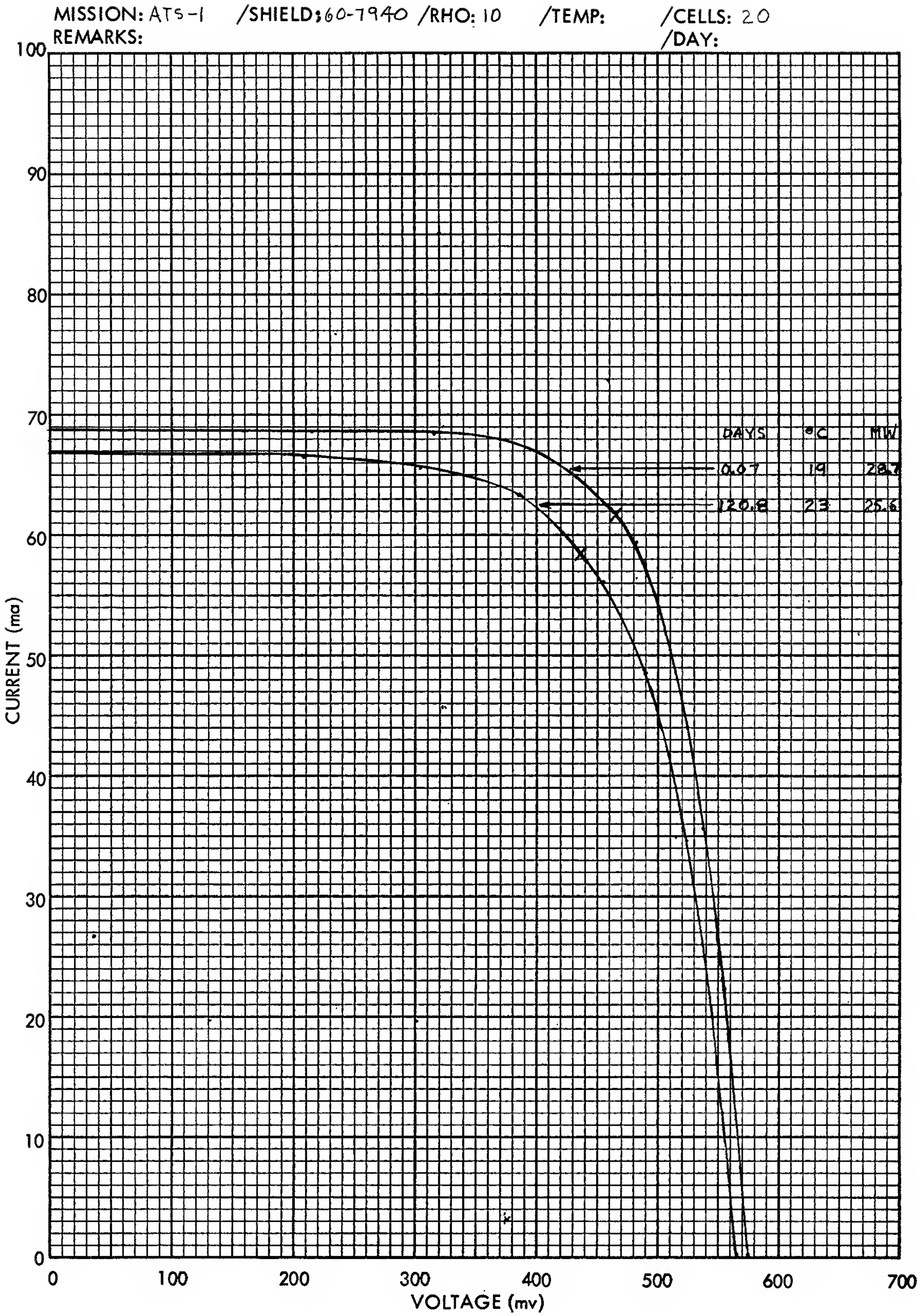

MISSION: ATS-1 /SHIELD: 60-7940 /RHO: 10 /TEMP: /CELLS: 20
REMARKS: /DAY:
DAYS °C MW
0.07 19 28.7
120.8 23 25.6
CURRENT (ma)
VOLTAGE (mv)
0
10
20
30
40
50
60
70
80
90
100
0
100
200
300
400
500
600
700

Figure 16

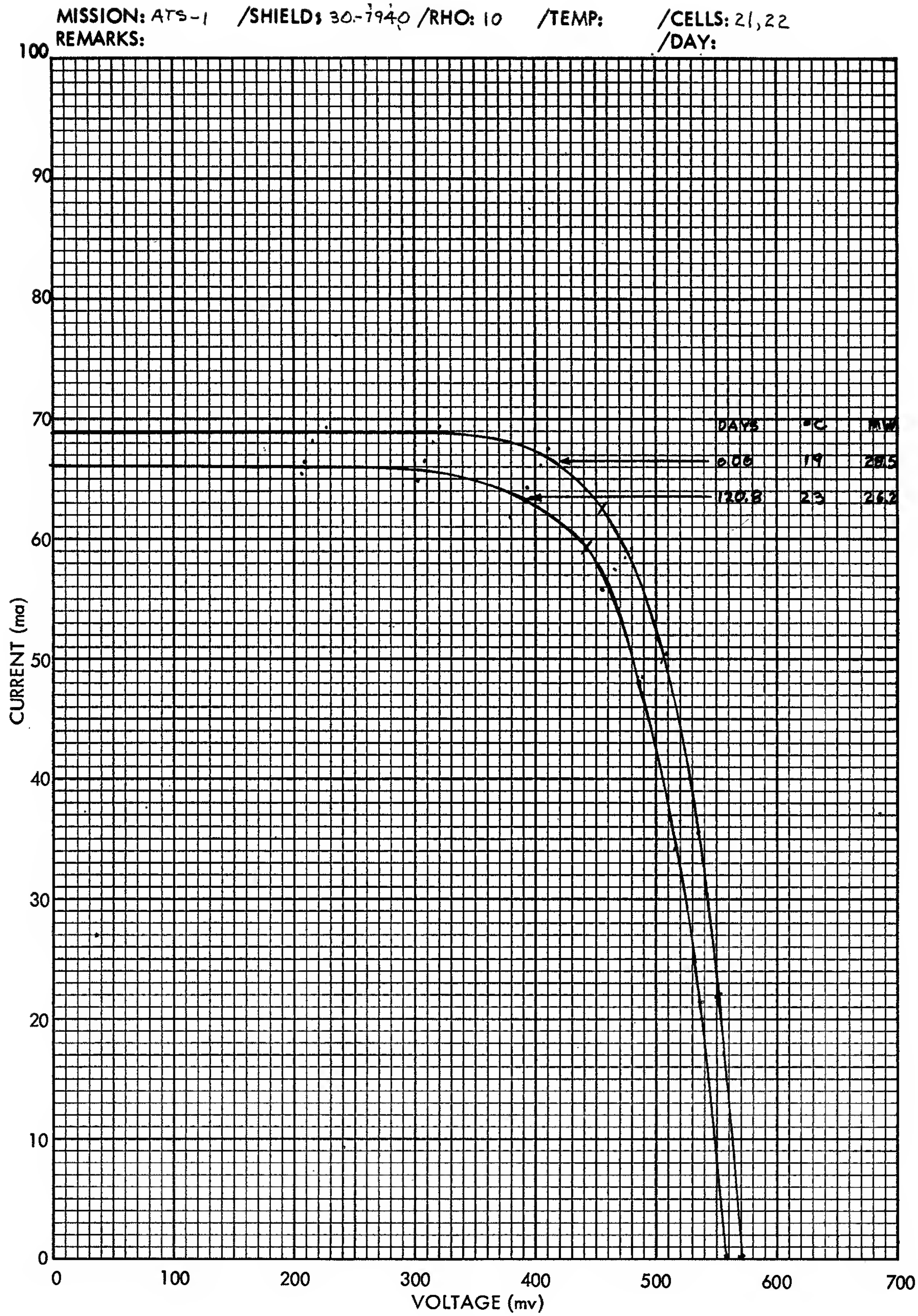
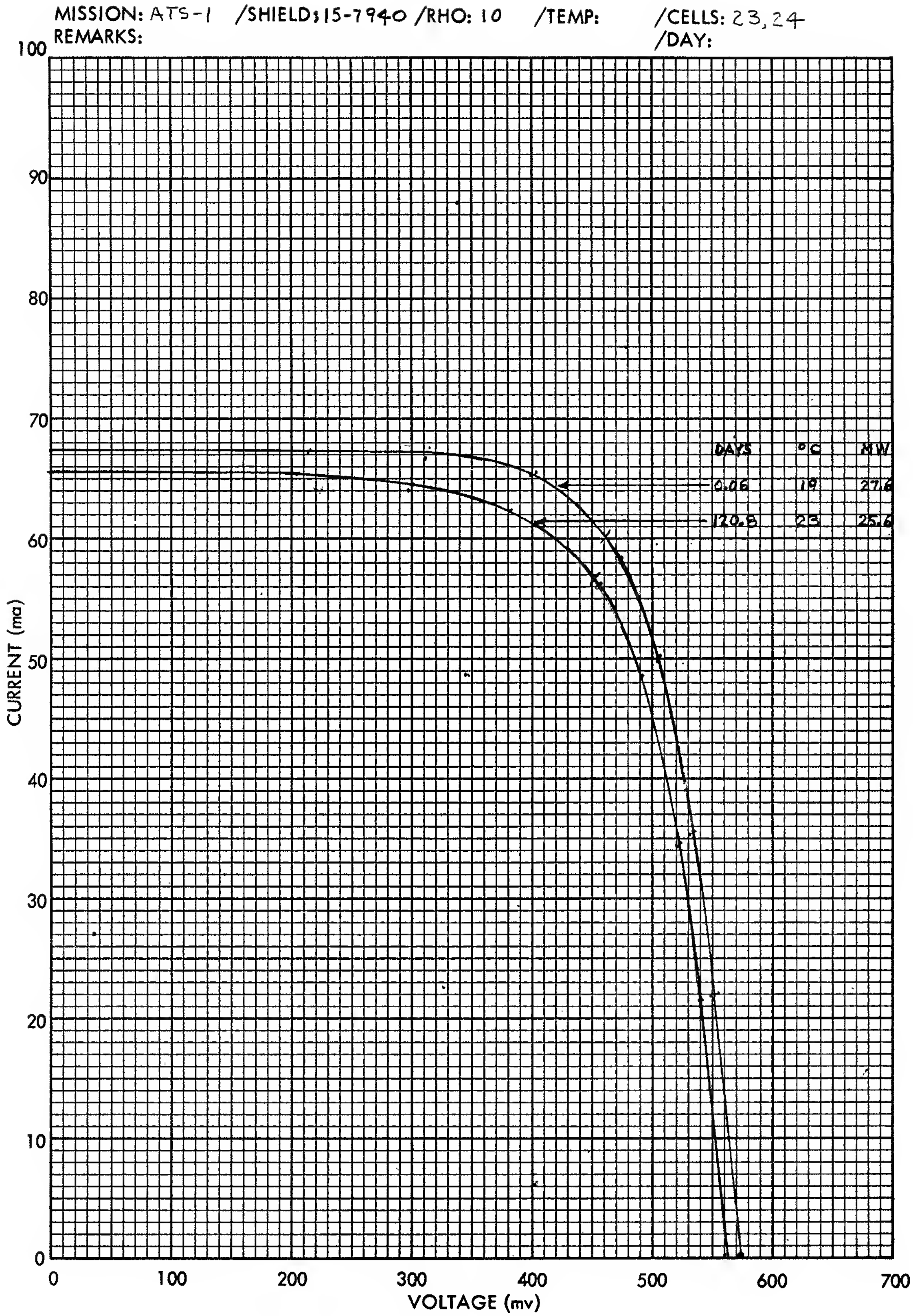

MISSION: ATS-1 /SHIELD: 30-1940 /RHO: 10 /TEMP: /CELLS: 21,22
REMARKS: /DAY:
DAYS °C MW
006 19 28.5
120.8 23 26.2
CURRENT (ma)
VOLTAGE (mv)
0
10
20
30
40
50
60
70
80
90
100
0
100
200
300
400
500
600
700

Figure 17



MISSION: ATS-1 /SHIELD; 15-7940 /RHO: 10 /TEMP: /CELLS: 23, 24
REMARKS: /DAY:
DAYS °C MW
0.06 19 27.6
120.8 23 25.6
CURRENT (ma)
VOLTAGE (mv)
0
10
20
30
40
50
60
70
80
90
100
0
100
200
300
400
500
600
700

Figure 18

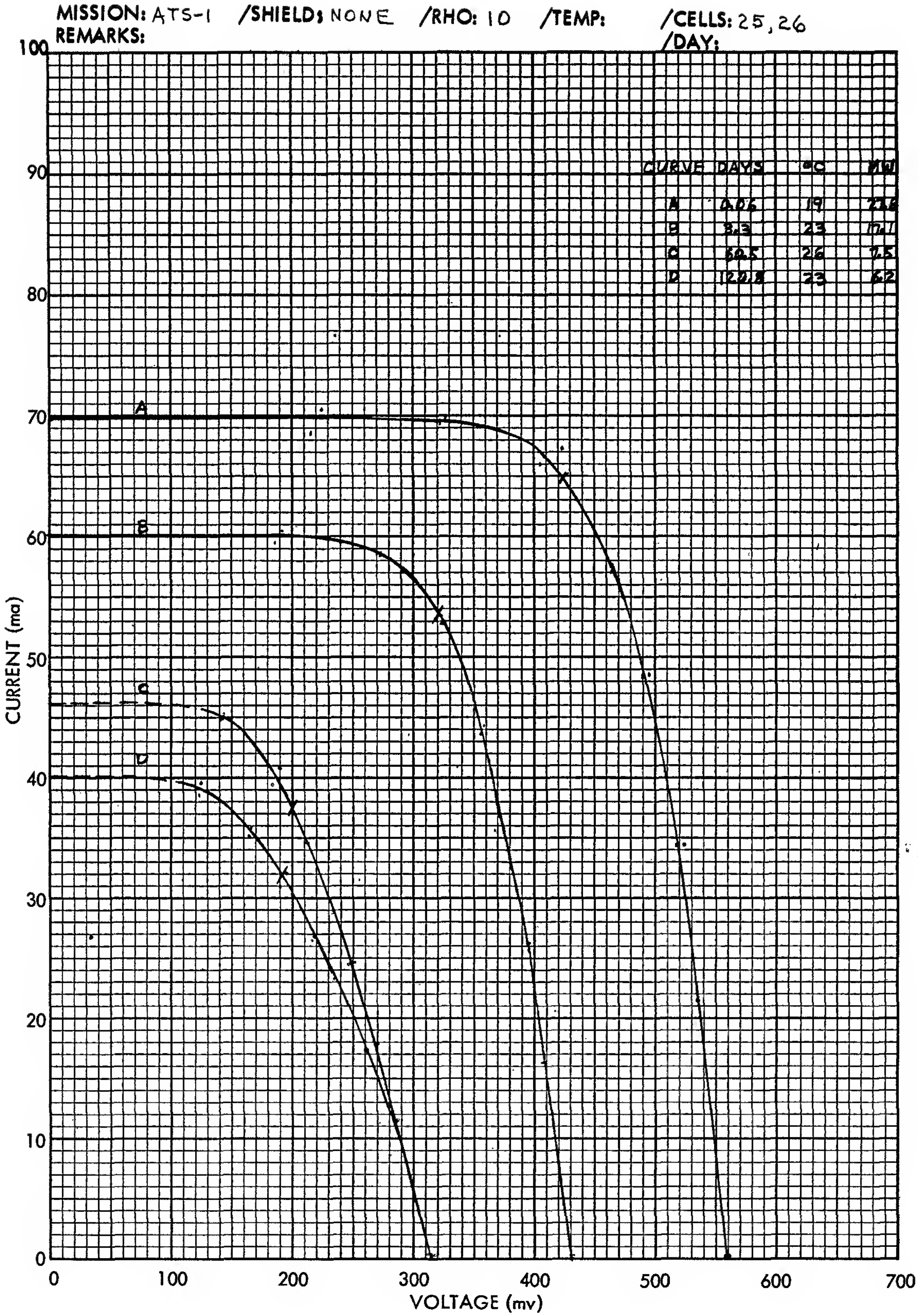
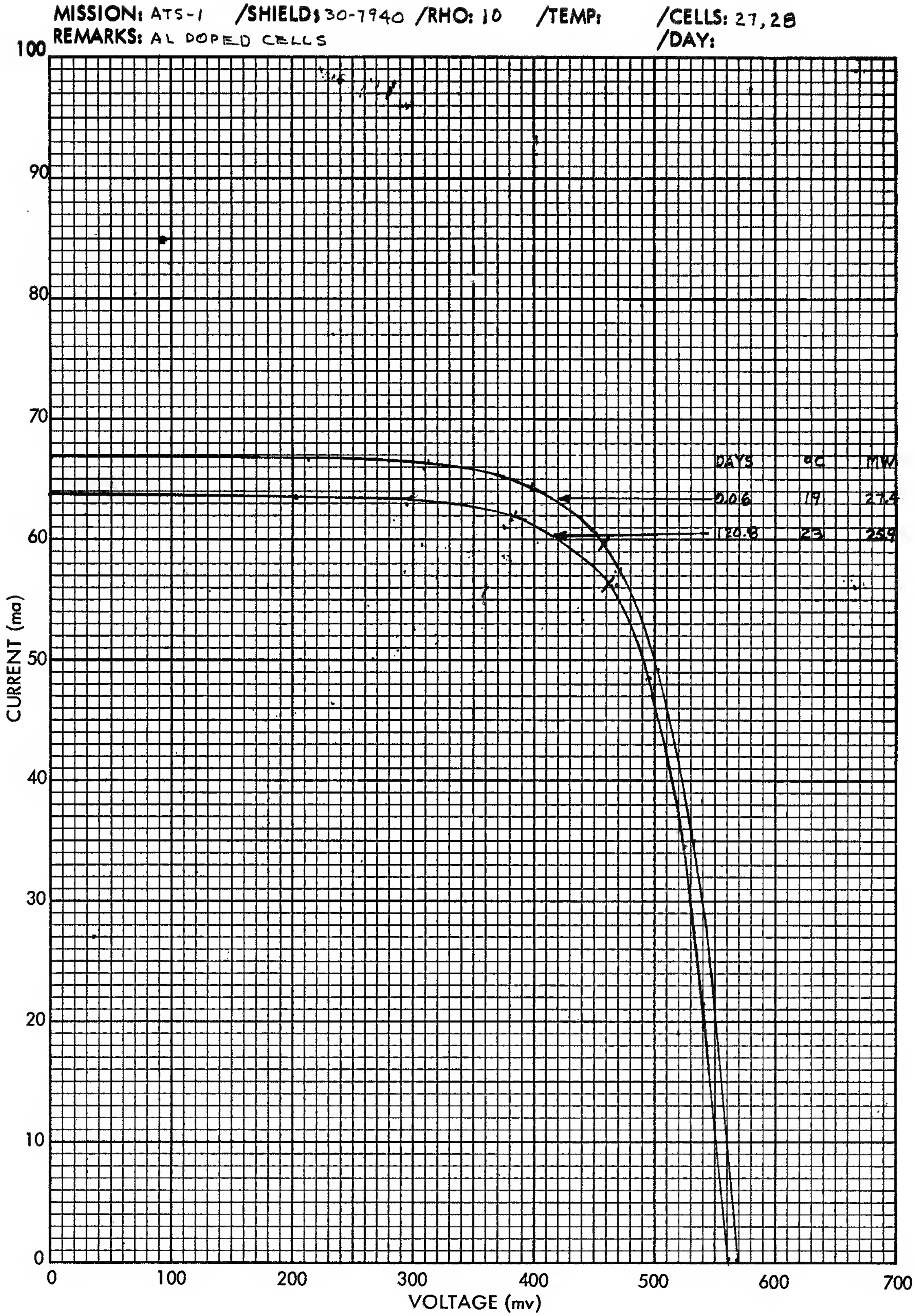
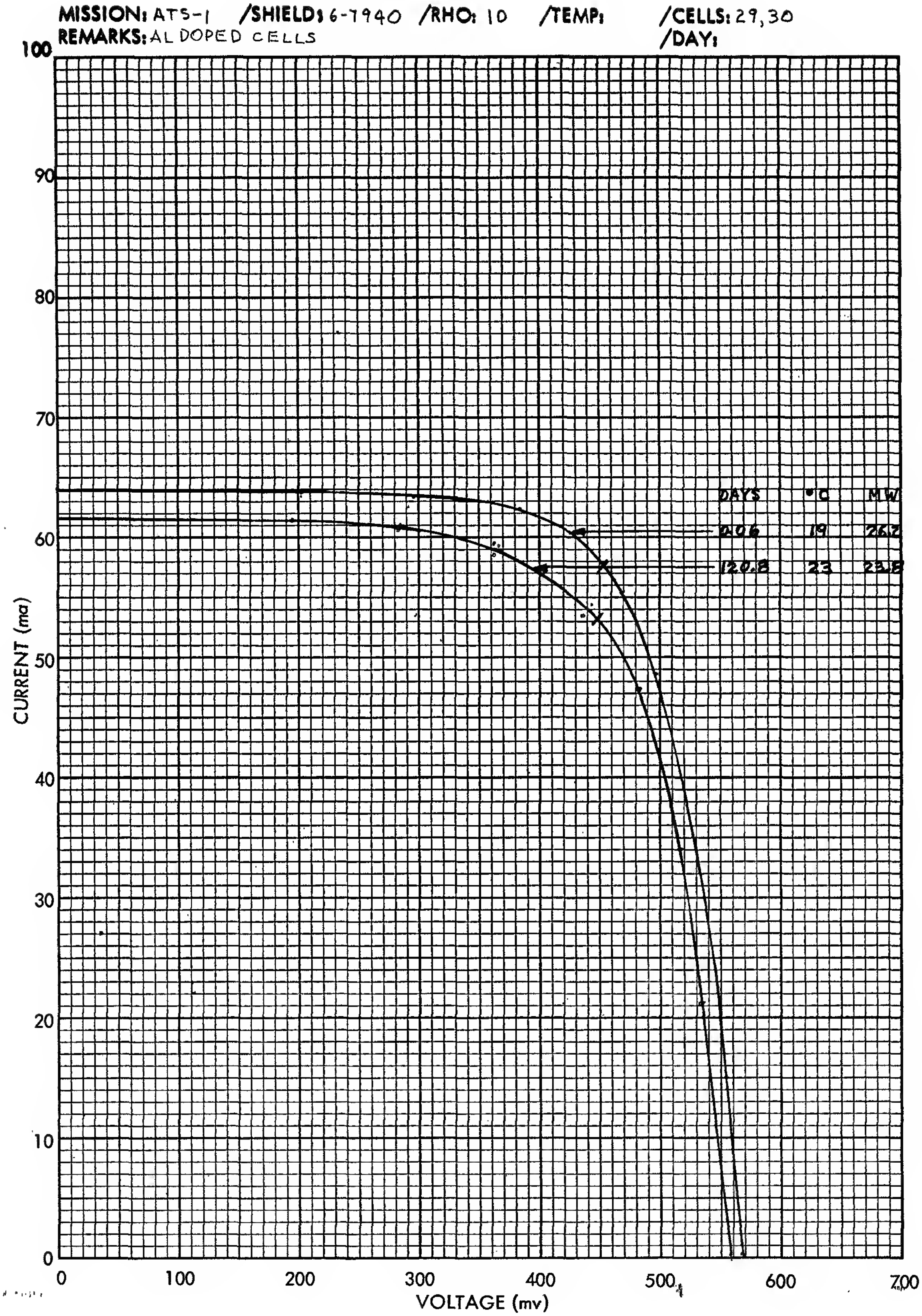

MISSION: ATS-1 /SHIELD: NONE /RHO: 10 /TEMP: /CELLS: 25, 26
REMARKS: /DAY:
CURVE DAYS °C MW
A 0.06 19
B 3.3 23 17.1
C 60.5 26 7.5
D 120.8 23 6.2
A
B
C
D
CURRENT (ma)
VOLTAGE (mv)
0
10
20
30
40
50
60
70
80
90
100
0
100
200
300
400
500
600
700

Figure 19



MISSION: ATS-1 /SHIELD: 30-7940 /RHO: 10 /TEMP: /CELLS: 27, 28
REMARKS: AL DOPED CELLS /DAY:
DAYS °C MW
0.06 19 27.4
120.8 23 25.9
CURRENT (ma)
VOLTAGE (mv)
0
10
20
30
40
50
60
70
80
90
100
0
100
200
300
400
500
600
700

Figure 20



MISSION: ATS-1 /SHIELD: 6-7940 /RHO: 10 /TEMP: /CELLS: 29,30
REMARKS: AL DOPED CELLS /DAY:
CURRENT (ma)
VOLTAGE (mv)
DAYS °C MW
206 19 26.2
120.8 23 23.8

Figure 21